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Hydrocarbon–Fueled Ramjet/Scramjet Technology Program
Phase II Extension Final Report

PREFACE

This report summarizes the results of work performed under an extension to Phase II of the hydrocarbon–fueled ramjet/scramjet technology program conducted by the United Technologies Research Center (UTRC), East Hartford, Connecticut. It supplements earlier results of the program which were previously reported in a Phase II Technical Progress Report (NASA CR–182042, July 1990). This work was performed under NASA Contract NAS1–17794 with partial funding provided by the Air Force Wright Laboratories. The work was performed in the time period from August 1990 to May 1992 under the joint technical coordination of G. B. Northam of the NASA Langley Research Center (NASA/LaRC), Hampton, Virginia and J. R. Smith of the Air Force Wright Laboratories, Wright–Patterson AFB, Ohio. The program manager at UTRC was A. J. Karanian. The principal investigator at UTRC was I. W. Kay. Major technical contributions were made by the following individuals at UTRC: R. N. Guile, W. T. Peschke and C.E. Kepler (engineering support), R. P. C. Lehrach (performance evaluation), J. S. Fournier (data reduction), J. P. McNamara (facility support), D. J. Bombara (hardware design) and P. R. Hamel (technical services).

ABSTRACT

The United Technologies Research Center conducted an experimental program to develop technology for a hydrocarbon-fueled ramjet/scramjet engine for operation at flight Mach numbers up to 7. As part of this program, connected-pipe combustion tests of key pilot and fuel injector components were performed in a variable-geometry two-dimensional test section over a range of combustor entrance conditions simulating the intended flight regime. A novel supersonic-inlet, air-breathing pilot was developed under the program that also incorporates an external mainstream fuel injector which serves as a primary fuel injection stage for the supersonic combustor.

In previous tests at simulated Mach 5.6 flight conditions (comprising a combustor entrance Mach number of 3.0), it was demonstrated that the pilot promoted efficient combustion of gaseous ethylene that was injected into the supersonic mainstream flow as a primary fuel. The idea of using the air-breathing pilot and distributed secondary fuel injection to achieve efficient supersonic combustion of ethylene over a wide range of equivalence ratios was also experimentally demonstrated; during tests with staged fuel injection, high secondary fuel combustion efficiencies were achieved and smooth transitions from fully supersonic to mixed mode (supersonic/subsonic) operation were demonstrated at high overall equivalence ratios. The air-breathing pilot was also shown to effectively isolate the inlet from the combustion process even at the high combustor pressures experienced during mixed mode operation. Most of the testing was done with gaseous ethylene fuel which was chosen to simulate both prevaporized liquid fuels and the gaseous products of the endothermic reaction of liquid hydrocarbon fuels. Limited combustor testing was done with liquid hydrocarbon fuels. Recent work, which is the subject of this report, was done to expand the related data base with liquid hydrocarbon fuels and to investigate the effects of a wider variety of combustor configurations and entrance conditions on component and combustor performance.

INTRODUCTION

Missile applications exist which require the performance benefits offered by the supersonic combustion ramjet (scramjet) propulsion system. Because these applications impose demanding volume constraints, a strong motivation exists for the development of a hydrocarbon-fueled airframe-integrated scramjet. Although studies of supersonic combustion of hydrocarbon fuels have been performed intermittently over the past thirty years (Refs. 1–3), they have yielded only a limited design data base. For example, UTRC conducted an extensive ground-based experimental investigation of hydrocarbon-fueled scramjet technology under Air Force sponsorship from 1968 to 1972 (Refs. 4,5). The results of those early tests clearly demonstrated that supersonic combustion of various hydrocarbon fuels could be achieved, although for many test conditions, special externally-mounted piloting devices were required to initiate and stabilize the flame.

In order to provide a firm technology base for the development of a mixed-mode subsonic/supersonic combustion hydrocarbon-fueled propulsion system, which could operate effectively without the need for external pilots, a Hydrocarbon-Fueled Ramjet/Scramjet Technology Program was undertaken at UTRC. The program was carried out in two phases: Phase I (Refs. 6,7) consisted of a study to identify and evaluate airframe/engine configurations satisfying performance and packaging constraints typical of a surface-launched missile application. A combustor concept was formulated and several potential schemes to enable efficient supersonic combustion of hydrocarbon fuels were evaluated. A staged-injection supersonic combustor employing a novel air-breathing pilot (Ref. 8) was selected as an effective approach to meeting the propulsion system needs and a plan was defined to develop and demonstrate this critical technology under Phase II of the program. Phase II was an experimental program devoted to the development of the air-breathing pilot and the subsequent use of this pilot to initiate and sustain efficient supersonic combustion. In the first part of Phase II, a thorough evaluation of the selected scramjet combustor concept was performed through a series of direct-connect tests at simulated Mach 5.6 flight conditions. As a result of these tests, important combustor and combustor component design criteria were developed and high levels of combustor performance were achieved (Refs. 9–11).

Under the latest phase of the experimental study, the development work was extended to cover wider ranges of simulated flight conditions and combustor geometries and a wider variety of hydrocarbon fuels. In a hydrocarbon-fueled scramjet vehicle, the liquid fuel would likely be used as a coolant and the absorbed heat would be used to vaporize and/or support the endothermic reaction of the fuel. Accordingly, in much of the development work, gaseous ethylene was used as a surrogate fuel intended to represent vaporized liquid fuel or the products of the endothermic reaction of a liquid hydrocarbon fuel. Additional testing was also done directly with various liquid hydrocarbon fuels that were heated and vaporized in a facility heater to simulate flight-type injection conditions. This report includes descriptions of the facilities and models used in the recent experiments and the results of combustion tests that were performed under this phase of the test program.

FACILITY/MODEL DESCRIPTIONS

The experimental program was performed in a connected-pipe type ramjet/scramjet test facility located at UTRC. During this program, two different facility air heaters were used to preheat the inlet air to the desired combustor entrance conditions. During the earlier Phase II tests, a Jet-A fueled-vitiating air heater was used. This heater has maximum operating pressure and temperature limits of 350 psig and 3000 R, respectively. For the present tests, a hydrogen-fueled vitiating air heater capable of simulating combustor entrance conditions corresponding to higher flight Mach numbers (up to approximately 7) was substituted for the hydrocarbon-fueled heater. The hydrogen-fueled vitiating heater has maximum operating pressure and temperature limits of 1500 psig and 4500 R, respectively. In both heaters, make-up oxygen is used to replenish the oxygen consumed in the combustion process and to restore the oxygen concentration in the heated products to twenty-one mole percent.

The tests described herein were conducted in two-dimensional hardware to allow the widest possible range of flexibility in varying the geometry of the test configurations. The applicability of the two-dimensional test results to the actual engine configuration, which was designed to employ a circular cross-section combustor (Ref. 6), was ensured by maintaining a proper simulation of combustor entrance conditions (i.e., Mach number, pressure and temperature) and local fuel distributions in the regions surrounding the pilot and fuel injector components and by preserving the actual length scale in the two-dimensional test configuration. The test section is uncooled and is 6-in wide. In this installation, candidate pilot and fuel injector configurations can be interchanged and the lateral and axial spacings between those elements can be varied to closely simulate the spatial patterns appropriate to an actual engine. The variable geometry features (1) afford a convenient means for varying the divergence angle of the upper wall of the test section as a way to evaluate the anticipated strong effect of the rate of increase of combustor area ratio on flame propagation rate and (2) provide an efficient means of parametrically determining the requirements for staged fuel injection to achieve high combustion efficiency. A schematic diagram of the variable-geometry test section, in a nominal 2-deg/3-deg upper wall configuration, is shown in Fig. 1. Key dimensions of the test section corresponding to the different nominal upper wall configurations established during the test program are listed in Table 1.

The basic configuration of the supersonic inlet pilot (Fig. 2) comprises a surface-mounted, eighteen-degree half-cone forebody followed by a combustion chamber formed by a semiconical cowl covering a recessed region of the wall. The overall length of the pilot (including the forebody) is approximately 3.5 inches. In concept, airflow enters the pilot inlet and is diffused to subsonic conditions where injected fuel autoignites and burns. The pilot models used in this program were also provided with a capability for mounting bluff body flameholders of various geometries through the floor of the pilot at variable insertion heights to assist in the autoignition and flame stabilization processes. The exhaust products rejoin the main combustor flow by exiting through a choked nozzle. In an actual scramjet engine, a number of such pilots would be located at the combustor entrance station, with each pilot sized to ingest less than three percent of the supersonic mainstream flow; the pilot structures would be fuel cooled, similar to the configuration tested earlier (Ref. 10).

Table 1. – Test Section Dimensions
(6–in. wide duct)

Combustor Configuration		Nozzle Exit	Minimum Area	Pilot Exit		Intermediate Joint	Combustor Exit
				Flush	Ramped		
	X (in)	0.000	11.187	13.075	14.625	33.187	64.560
2–deg/3–deg (nominal)	h (in)	3.000	2.750	2.804	2.848	3.378	5.13
1.64°/3.21° (actual)	A (in^2)	18.000	16.500	16.824	17.088	20.268	30.834
2–deg/2–deg (nominal)	h (in)	3.000	2.750	2.804	2.848	3.378	4.271
1.64°/1.64° (actual)	A (in^2)	18.000	16.500	16.824	17.088	20.268	25.626
1–deg/4–deg (nominal)	h (in)	3.000	2.750	2.772	2.790	3.006	5.139
1.64°/1.64° (actual)	A (in^2)	18.000	16.500	16.632	16.740	18.036	30.834
2.5–deg/2.5–deg (nominal)	h (in)	3.000	2.750	2.835	2.904	3.735	5.139
2.56°/2.56° (actual)	A (in^2)	18.000	16.500	17.010	17.424	22.410	30.834

During much of the connected–pipe test program, testing was done using a single full–scale, water–cooled model of the pilot. The use of water cooling, in lieu of fuel cooling, facilitated modification of the pilot hardware as it became necessary during the test program. The test section included provisions for mounting the pilot model in either a flush wall configuration or on a ramp which positioned the pilot entrance approximately 0.25 inches off the wall (partially out of the boundary layer) where it could capture higher energy flow. The ramp had an incline angle of 6–deg and was 1.75 inches wide. Mounting frames were also provided which allowed testing with a pair of water–cooled pilot models in either a flush–mount or ramp–mount configuration. In the dual ramp–mounted pilot configuration, the pilots were located side–by–side on individual ramps on the lower wall of the test section. In either of the dual pilot configurations, the centerline–to–centerline spacing of the pilots was three inches. Photographs showing the single and dual ramp–mounted pilot installations are presented in Figs. 3 and 4, respectively.

The primary fuel injection stage of the supersonic combustor of the UTRC engine concept entails external mainstream fuel injection from the cowl of the air–breathing pilot. To accommodate this scheme in the pilot models, a tubular injection manifold (0.080–in diameter) was flush mounted in the upstream portion of the water–cooled cowl. The primary fuel was injected from three holes (0.041–in diameter), located at top dead center and at forty–five degrees from top dead center on each side of the cowl and angled downstream at 60 degrees to the mainstream flow direction. In the single ramp–mounted pilot configuration, an alternative modified primary injection circuit was formed by adding two additional 0.041–in diameter holes to the existing primary injection circuit. The added injection holes were located on the top surface of the pilot ramp at its downstream end in line with the two intersections of the cowl and the ramp; they injected fuel normal to the airflow direction at an outboard angle of 60–deg (relative to the floor) – the injection point on the ramp was elevated approximately 0.64 inches off the floor of the test section. For tests using this injector, the primary fuel injected from the two added holes is referred to as "base" fuel and the primary fuel injected from the original holes is referred to as "cowl" fuel.

During the tests described herein, secondary fuel injection was always accomplished using a single lateral row of flush wall injectors that were located on the test section lower wall and injected fuel normal to the airflow direction. The secondary fuel injection row was located at one of the alternative axial sites denoted in Fig. 1. For all of the tests with the single flush–mounted pilot and for some of the tests with the single ramp–mounted pilot, the secondary fuel injector comprised a pair of 0.062–inch diameter orifices laterally spaced 3–inches apart straddling the test section centerline. For the remaining tests with the single ramp–mounted pilot and for all of the tests with the dual ramp–mounted pilots, an additional injection orifice was located on the lateral centerline of the secondary fuel injection row. Depending upon the particular test configuration, the diameter of the central injection orifice was either 0.041 inches or 0.062 inches.

Instrumentation provisions in the variable–geometry hardware include an extensive array of approximately 150 wall static pressure taps, distributed on the top and bottom walls of the test section, and two pairs of sidewall–mounted rectangular viewing windows in the vicinity of the pilot and fuel injector locations.

PROCEDURES

During the connected-pipe test program, test durations in the heat-sink hardware were generally in the range from one to two minutes. Observations of the combustion processes were made through the sidewall windows and performance evaluations were made for steady-state operating periods on the basis of calculated air and fuel flow rates and measured wall static pressures within the pilot and throughout the test section.

Captured pilot mass flow rates were estimated using measured boundary layer characteristics and previously acquired cold flow calibration data. Pilot performance evaluations were based on one-dimensional calculations which presumed that choked flow conditions existed at the pilot exit area. Under that assumption, pilot exhaust temperatures were calculated on the basis of the estimated air flow rate, the measured pilot fuel flow rate and measured internal pilot pressures. This procedure is described in more detail in Ref. 11. For cases corresponding to the ramped pilot installation, the pilot mass flow estimates were based on separate measurements of the local pitot pressure and stagnation temperature profiles that were made at the pilot entrance station on the ramp.

Mainstream combustor performance evaluations were performed by comparing measured test section pressure-area integrals with analytical values calculated for the same conditions using a UTRC one-dimensional cycle analysis code, RASCAL. For this purpose, both the experimental and the analytical pressure-area integrals were normalized with respect to a condition with no pilot or mainstream fuel. For tests at higher equivalence ratios in which mixed-mode combustion occurred, the analysis imposed a pre-combustion shock at the pilot exit station to simulate the resulting experimental pressure distributions. The strength of the shock was related to the total amount of reacted fuel in accordance with a minimum entropy solution to the governing equations (Ref. 12).

BASELINE PERFORMANCE

The pilot development and combustor evaluation tests performed under the first part of Phase II of this program were conducted at a single combustor entrance condition simulating flight at Mach 5.6. These combustor entrance conditions comprised a Mach number of 3.0, a stagnation temperature of 2675 R and static pressure of 4.5 psia. During those tests, an air-breathing pilot configuration was developed that operated stably with ethylene fuel. It was shown to operate with minimal inlet flow spillage over a wide range of internal equivalence ratios at high pilot combustion efficiencies. Autoignition was readily achieved with the aid of an internal bluff-body flameholder but without the use of any external ignition devices or fuel additives. As developed, the selected pilot configuration produced a sonic exhaust stream having a stagnation pressure of approximately 25 psia and a stagnation temperature of approximately 4000 R. The hot pilot was subsequently shown to be very effective in promoting supersonic combustion of mainstream fuel (Ref. 10).

A baseline set of combustor pressure distributions measured on the lateral centerline of the lower wall of the test section during the early Phase II testing with ethylene fuel is presented for reference in Fig. 5. Although not presented herein, pressure distributions showing the same trends also were obtained for positions displaced laterally from the centerline and on the upper wall (see Ref. 11). As shown in Fig. 5, the pressure distribution corresponding to the pilot only condition (curve 1) shows that the combustor perturbations associated with the small, high-temperature pilot flow alone are small relative to the reference (heater only) pressure distribution. More significant pressure increases were measured under conditions of supersonic primary fuel combustion (curve 2) and both supersonic and mixed-mode combustion of staged primary and secondary fuel (curves 3 and 4). For the staged fuel injection cases, two generic types of wall static pressure distributions were measured during the test program. At lower secondary fuel flow rates, the pressure increases attributable to the secondary fuel combustion process always occurred downstream of the point of secondary injection and the peak pressures were consistently less than three times the combustor entrance pressure, P_{SO}. At higher secondary fuel flow rates, much larger pressure increases were measured (in the range from three to six times the combustor entrance pressure) and in those cases the disturbances were observed to propagate upstream of the point of secondary injection. The second type of combustor behavior was attributed to the formation of a "pre-combustion" shock in the test section just downstream of the pilot exit resulting in a mixed-mode combustion process. It is important to note that in both types of combustor flow, the combustor entrance conditions upstream of the pilot remained unperturbed in the presence of significant levels of primary and secondary combustion. It should also be noted that the mainstream equivalence ratios indicated in Fig. 5 are calculated on the basis of the total airflow in the entire 6-in wide by 3-in high test section. Since the injected fuel was concentrated in the region surrounding the pilot and the injectors, the overall values are significantly lower than the actual local equivalence ratios near those components. Although the local values would be more representative of the mixtures that would exist in an actual scramjet engine with a full complement of pilots and fuel injectors, those values are not known precisely. For consistency, all of the mainstream equivalence ratios cited in this paper are average overall values.

REPRODUCIBILITY OF COMBUSTOR PERFORMANCE

As part of the effort to extend the data base developed under Phase II of this program to a wider range of simulated flight conditions, the hydrocarbon-fueled vitiating air heater that had been used for all of the previous tests was replaced by the hydrogen-fueled heater for the remainder of the program. In order to establish whether the vitiator substitution had any effect on the results of the supersonic combustion experiments, the first tests performed with the hydrogen-fueled vitiator comprised a series of repeatability experiments. A typical early result of these experiments is presented in Fig. 6 in which data from two tests conducted at identical test conditions in the same test configuration are compared. As shown in Fig. 6, significantly lower combustor pressure rises were achieved when the hydrogen-fueled vitiator was used in comparison to the previous test in which a hydrocarbon-fueled vitiator had been used. Whereas the earlier results were characterized by a supersonic combustion efficiency of approximately 90 percent (Ref. 10), the results achieved with the hydrogen-fueled vitiator corresponded to a combustion efficiency of less than 50 percent. At higher mainstream equivalence ratios (not shown in Fig. 6), whereas sufficient heat release to cause mode transition had been achieved with the hydrocarbon-fueled vitiator, mode transition was not achieved at even higher equivalence ratios with the hydrogen-fueled vitiator.

Extensive experiments and analyses were performed to determine the causes of these differences in the supersonic combustion test results. Some of these diagnostic experiments involved investigations of the sensitivity of combustor performance to the actual exhaust temperature of the air-breathing pilots as pilot temperatures lower than the nominal 4000 R operating condition were measured in some of the earlier tests with the hydrogen-fueled vitiator. Tests were conducted in which a wide range of pilot operating conditions were created by varying the pilot flameholder configuration and/or the pilot fuel. Although these tests did succeed in creating pilot exit temperatures that duplicated or exceeded the levels established during the tests with the hydrocarbon-fueled vitiator, those perturbations failed to resolve the differences in the associated supersonic combustion results.

Examination of the heater characteristics for a large number of tests showed that the hydrogen-fueled vitiator was operating at a combustion efficiency (corrected for wall heat loss) of 100 percent compared to the 95 percent level previously measured for the hydrocarbon-fueled vitiator. With this difference in mind, an analytical effort was initiated to evaluate the effects that differences of the products of the two facility vitiating air heaters might have on the ignition and combustion of hydrocarbon fuel in the scramjet combustor. These studies were performed by running a chemical kinetics code (Chemkin) in a perfectly-stirred reactor mode with input species comprising mixtures of the frozen products of combustion of the vitiating air heaters (at various efficiency levels) and the mainstream ethylene fuel. Typical ignition delay times predicted by this analysis are presented in Table 2 for two different assumed inlet temperatures bracketing the actual combustor inlet conditions. It can be seen that for vitiators operating at 100 percent efficiency, the effect of the vitiator fuel type on the resulting ethylene ignition delay time was very small. However, for a hydrocarbon-fueled vitiator operating at an efficiency of 95 percent, the effect of the presence of many partially fragmented reactive molecules in the exhaust products (albeit at small concentrations) was found to reduce the predicted ignition delay times for the injected scramjet fuel by approximately fifty percent.

Table 2. – Calculated Ignition Delay Times (at test section conditions)

Perfectly stirred reactor – Ethylene fuel (Φ = 0.5)
Static pressure = 0.4 atm

Vitiator Conditions	T_o = 2430 R	T_o = 2700 R
Hydrogen fuel – 100% efficiency	4.85 msec	0.477 msec
Jet–A fuel – 100% efficiency	4.89 msec	0.474 msec
Jet–A fuel – 95% efficiency	2.63 msec	0.278 msec

A critical series of diagnostic tests were performed to confirm the above–described analytical results. In these tests, a small quantity of silane was added to the primary ethylene fuel used in the scramjet combustor (in a manner which did not significantly change the fuel penetration or mixing characteristics) in an effort to simulate the chemical kinetic effects of the presence of reactive partially fragmented hydrocarbon molecules in the combustor entrance flow. When tests were conducted using the silane–doped ethylene fuel, the levels of heat release achieved as a result of the primary fuel combustion process increased significantly; in addition, at higher mainstream equivalence ratios, achieved by injecting additional undoped secondary ethylene fuel into the combustor (with the secondary injector located at X_{sec} = 14 inches), the levels of heat release achieved were sufficiently high to induce mode transition in the scramjet combustion process. As shown in Fig. 7, the combustor pressure rises achieved with the silane–doped fuel closely paralleled the results previously achieved with neat ethylene fuel in the same configuration using the hydrocarbon–fueled vitiator. This result supports the conclusion that the previously reported baseline supersonic combustion data, achieved using the hydrocarbon–fueled vitiator, were acquired under simulated combustor entrance conditions that unduly enhanced the ignition and combustion of the injected ethylene fuel. Accordingly, testing was continued using the hydrogen–fueled vitiator, a configuration that provides a better simulation of conditions as they would exist in flight.

COMBUSTOR DEVELOPMENT TEST RESULTS - $M_0 = 5.6$

Following the above-described resolution of the differences between the results achieved using the different vitiating air heaters, the planned connected-pipe test program was continued using the hydrogen-fueled vitiator. These tests were focussed on developing higher baseline levels of combustor performance with ethylene fuel at the simulated Mach 5.6 flight condition. Accordingly, the effects of varying some critical combustor design parameters were investigated. These changes comprised modification of the test section wall contour, relocation of the air-breathing pilot out of the combustor boundary layer and replacement of the single air-breathing pilot installation with a configuration including a pair of side-by-side pilots. The results of these tests are discussed below. A comprehensive listing of the test configurations and conditions for these tests along with a summary of the calculated fuel equivalence ratios and combustor pressure-area integrals for the steady-state portions of the tests (denoted by data "burst") is presented in the Appendix.

Combustor Wall Contour Variations

The wall contour tests were performed at simulated Mach 5.6 flight conditions (combustor entrance Mach number = 3.0) using ethylene fuel and the same pilot and mainstream fuel injectors as used in the baseline configuration tests. The wall contour was initially modified from the baseline configuration, which comprised nominal initial/final upper wall divergence angles of 2-deg/3-deg (see Fig. 1), to a 1-deg/4-deg configuration having the same overall combustor exit/entrance area ratio. The supersonic combustion process was very sensitive to the initial wall divergence angle. In the 1-deg/4-deg duct, efficient combustion of neat ethylene fuel was achieved at Mach 3 combustor entrance conditions. However, in this configuration, mode transition repeatably occurred at a relatively low overall equivalence ratio of approximately 0.16. In order to provide a test configuration that would promote efficient combustion over a wider supersonic-mode operating range, a second change in the wall contour, to a nominal 2-deg/2-deg configuration (corresponding to a straight upper wall) was made. This test section had a smaller exit-to-entrance area ratio than the baseline (1.4 versus 1.7), but a more accommodating initial divergence angle. As shown in Fig. 8, in the 2-deg/2-deg test section, the combustor pressure rises increased steadily with increasing equivalence ratio and the combustor could be operated in the supersonic mode up to a higher equivalence ratio of approximately 0.22 before mode transition occurred. The combustion results achieved with this alternative wall contour were significantly better than those achieved in the baseline 2-deg/3-deg test section configuration. In the baseline configuration, combustion efficiencies of less than 50 percent had been achieved with the hydrogen-fueled vitiator; with a straight 2-deg upper wall, these levels increased to the same 80 to 100 percent range that had previously been achieved with the hydrocarbon-fueled vitiator. Further, whereas sufficient heat release to cause mode transition could not be achieved with neat ethylene fuel in the baseline configuration, mode transition was repeatably achieved in the alternative configuration.

Single Ramp-Mounted Pilot Tests

As described previously, provisions were included in the test section to alternatively install the air-breathing pilot on a 6-deg inclined ramp instead of flush with the lower wall. When mounted to the ramp, the pilot captured higher energy flow as its entrance station was located off the wall and some of the lower energy boundary layer flow spilled off the sides of the 1.75-in wide inclined ramp before being captured. Pilot combustion tests of the ramped configuration were conducted with ethylene fuel in the 2–deg/2–deg test section. A dramatic improvement in the operational characteristics of this pilot relative to the baseline flush–mounted installation was revealed during these combustion tests. In the ramp–mounted configuration, autoignition and stable operation of the pilot were achieved with ethylene fuel without the assistance of the bluff–body flameholder that had previously been required in the flush–mounted pilot installations. Calculated mass flow rates, based on boundary layer measurements made on the ramp, were approximately 75 percent higher than those similarly calculated for the flush–mounted pilot configuration. Accordingly, the ramp–mounted pilot was operated at proportionally higher ethylene fuel flow rates so as to maintain the same internal equivalence ratio. The ramp–mounted pilot produced gases having an exit stagnation temperature of approximately 4000 R; that value was calculated on the basis of the derived mass flow rates and internal pressure measurements.

Combustor pressure distributions for cases where the ramp–mounted pilot was operated in conjunction with primary and secondary (X_{sec} = 14 inches) ethylene fuel injection over a range of mainstream equivalence ratios are presented in Fig. 9. Although the baseline (no–fuel) pressure distribution for the ramp–mounted pilot configuration differed significantly from that for the flush–mounted pilot (because of the different blockage characteristics), it can be seen that the pressure rises attributable to mainstream combustion once again increased steadily with increasing ethylene equivalence ratio. In this configuration, the combustor could be operated in the supersonic mode up to an equivalence ratio of approximately 0.25 before mode transition occurred. At the highest equivalence ratio tested (0.295), a maximum combustor pressure rise of approximately 5.6 was achieved. Even at that high a level, the air–breathing pilot was effective in isolating the combustion process from the inlet ducting as evidenced by a lack of any perturbations in the pressures upstream of the pilot exit station. Calculated combustor pressure–area integrals (normalized to the no–fuel condition) for the cases shown in Fig. 9 were in the same range as those achieved under similar conditions with the flush–mounted pilot.

As a preliminary effort to improve the combustor performance achieved with the ramp–mounted pilot configuration, tests of a modified fuel injector including additional injection ports on the ramp (as described previously) were performed with ethylene fuel over a wide range of total equivalence ratios. During initial tests, it was found that the combustor pressure rises achieved with the modified primary fuel injector did not change significantly from those achieved with the baseline fuel injection configuration (i.e, with no additional "base" fuel) at the same overall equivalence ratio. However, during separate tests with the ramp–mounted pilot involving primary fuel injection only, it was found that somewhat higher combustor pressure rises (corresponding to an approximate 10 percent increase in the normalized combustor pressure–area integral) could be achieved by increasing the "base–to–cowl" fuel flow ratio above the nominal 2/3 value. Although these results are preliminary, they suggest further modification of the fuel distribution among the various injection sites could be expected to produce additional significant improvements in combustor performance.

Dual Ramp–Mounted Pilot Tests

Connected–pipe tests were also performed with a combustor configuration comprising dual, side–by–side, ramp–mounted pilots. These tests were intended to create higher heat release rates in the test section than could be provided by a single pilot and which would provide a better simulation of the heat release levels that would exist in an actual combustor with a full complement of pilots and fuel injectors. In the dual installation, the ramp–mounted pilots were spaced 3–in. apart (center–to–center) on the lower wall of the test section. All of the dual-pilot tests were conducted exclusively with gaseous ethylene fuel and at conditions simulating flight at a Mach number of 5.6. As was done with the single pilot, primary fuel was injected through three 0.041-in. diameter orifices on the outside of each pilot cowl. Secondary fuel injection was accomplished through a single row of three flush mounted 0.063-in. diameter orifices located on the lower wall of the test section at various axial distances downstream of the pilot exit station. Two of the injection orifices were aligned with the axial centerlines of the pilots while the third was on the lateral centerline of the test section. The test section wall contour was systematically varied during this test series.

The initial tests of the dual-pilot configuration were conducted in a test section with a constant two-degree upper wall divergence angle with the secondary fuel injection stage located approximately one inch downstream of the pilot exit station. In this configuration, autoignition of ethylene injected into the dual pilots was readily achieved and the hot pilots successfully promoted supersonic combustion of mainstream fuel. Combustor wall static pressure distributions measured over a range of equivalence ratios during this dual-pilot test are presented in Fig. 10. It can be seen that large pressure increases indicative of a transition to mixed mode operation were experienced at a relatively low overall equivalence ratio of approximately 0.20. The combustor then operated stably in the mixed mode up to an equivalence ratio of approximately 0.31 after which further increases in fuel flow rate produced pressure perturbations upstream of the pilot indicative of the onset of an inlet "unstart" condition. However, even in this condition the disturbances were contained within the short isolation duct between the facility nozzle and the combustor entrance station.

Following these tests, the combustor wall contour was modified by increasing the upper wall divergence angle in the downstream portion of the test section from two degrees to three degrees in an effort to create a geometry that would accommodate more heat release without inducing inlet unstart. In this configuration, although the pressure distributions in the aft section of the combustor exhibited a more rapid decay rate (as anticipated), the onset of mode transition and inlet unstart occurred at approximately the same overall equivalence ratios as in the straight two-degree combustor.

An additional test series was then conducted with the dual, ramp-mounted pilot combustor in which the secondary fuel injection stage was moved downstream by approximately eight inches. This arrangement was intended to allow for the combustion of greater quantities of secondary fuel without inducing inlet unstart. With this fuel injection arrangement, a series of tests were conducted with three different test section wall contours comprising initial/final divergence angles of 2-deg/2-deg, 2-deg/3-deg and 2.5-deg/2.5-deg. In the straight 2-deg combustor, the downstream movement of the secondary injection stage delayed the onset of both mode transition and inlet unstart to significantly higher overall equivalence ratios of approximately 0.24 and 0.40, respectively. In the 2-deg/3-deg combustor, although mode transition occurred at approximately the same overall equivalence ratio of 0.24, further increases in the secondary fuel flow rate produced only small increases in combustor pressure and inlet unstart did not occur at the highest overall equivalence ratio that was established during the tests, approximately 0.43. In the straight 2.5-deg duct, the more rapid initial divergence produced maximum measured combustor pressure rises that were significantly lower than those experienced in either the straight 2-deg duct or the 2-deg/3-deg duct. In this configuration, the maximum combustor pressure rise ratio was approximately 4.5 and overall equivalence ratios as high as 0.47 were established without experiencing inlet unstart.

The results of this test series will aid in the formulation of design criteria applicable to a combustor having a full complement of pilots and fuel injectors. In such a combustor, the pilots and fuel injectors would be designed to distribute the fuel throughout the combustor and the combustor would be operated at higher overall equivalence ratios up to approximately 1.0. The data presented above demonstrate the critical sensitivity of the combustor performance to the combustor contour and the fuel injector distribution.

COMBUSTOR PERFORMANCE WITH LIQUID FUELS

In addition to the ethylene-fueled combustor performance tests described above, significant combustor testing also was performed under Phase II of this program in which Jet-A (JP-5), a liquid hydrocarbon, was used as the primary fuel (Ref. 11). During early tests in which the Jet-A was injected as an unheated liquid, very low combustion efficiencies (less than 30 percent) were achieved. In later tests, the Jet-A was injected as a preheated liquid so that it would flash-vaporize upon injection into the combustor. Using this injection scheme, fuel utilization efficiencies nearly identical to the levels achieved with gaseous ethylene fuel were achieved at low equivalence ratios but the Jet-A performance was found to decrease significantly at higher equivalence ratios. That drop in performance was attributed to mixing limitations associated with the suspected poor penetration characteristics of a flash-vaporizing jet in a supersonic stream.

In an effort to improve the combustor performance levels achieved with liquid hydrocarbon fuels at high equivalence ratios, an additional test series was performed as part of the current program. During these tests liquid JP-7 fuel was preheated and prevaporized in an electrically powered resistance heater prior to injection. Prevaporization conditions were ensured when the injection temperatures were maintained in the range from 1200 to 1600 deg R. The tests were performed using the ramp-mounted pilot configuration with the same baseline mainstream fuel injector arrangement that had previously been used with unheated gaseous ethylene fuel. The combustor wall contour comprised a straight 2-deg upper wall. For comparison, additional combustion tests were also conducted in which gaseous ethylene was heated to similar temperatures and used as the mainstream test fuel. Although the effects of fuel temperature alone on combustor performance were found to be very small with ethylene fuel, the data base so developed served as an important baseline for direct comparisons with the liquid fuel test results. In all of these tests the pilot fuel was unheated gaseous ethylene. Detailed summaries of the results of the fuel-type tests described above are included in the Appendix.

A comparison of supersonic-mode combustor pressure distributions measured with heated JP-7 and heated ethylene at the same equivalence ratio and injection temperature is presented in Fig. 11. For the JP-7 case, the integrated combustor pressure rise is approximately 30 percent lower than that corresponding to the reference ethylene case. This performance decrement was attributed to fuel/air mixing limitations that resulted from poorer penetration of the injected JP-7. For gaseous injection from the same injection orifices, the jet penetration of the injected JP-7 was predicted to be approximately 65 percent of that for ethylene at the same fuel flow rate (because of the higher density of the JP-7 fuel and the resulting lower injection velocity). Although it was not demonstrated in these tests, it would be expected that with minor modifications to the mainstream fuel injectors, the gaseous JP-7 could readily be mixed and burned as effectively as gaseous ethylene. It should also be noted that for the tests with JP-7 fuel, the maximum fuel flow rate that could be established while maintaining gaseous injection conditions was limited by the 80-kw facility power supply used with the electrical fuel heater. Based on a comparison with the results acquired with ethylene fuel, that maximum JP-7 fuel flow rate was slightly less than the fuel flow rate that would have been necessary to achieve mode transition in the combustion tests.

An additional series of liquid fuel tests also were performed during this program with a fuel blend containing 90 percent by volume Jet-A and 10 percent by volume triethylamuminum (TEA), an ignition enhancing additive. The choice of this additive was based on recent tests that had shown that the addition of TEA to a hydrocarbon fuel could result in a reduction of overall reaction times by an order of magnitude (Ref.

13). Although those tests had been performed using blends containing a minimum TEA concentration of 50 volume percent, the present tests used a 10 percent blend in an effort to minimize the associated fuel handling and safety problems (the pyrophoric nature of the fuel blend decreases as the percentage of TEA decreases) and to obtain combustion results with a more logistically acceptable fuel. The tests were conducted in an identical manner to those described above for liquid JP-7. Similar fuel equivalence ratios and injection temperatures were established. As shown in Fig. 12, at similar conditions, the measured combustor pressure distributions with the Jet-A/TEA fuel blend were virtually identical to those achieved with the neat JP-7 fuel. Although this result may be partly attributable to the low TEA concentration in the fuel blend, it is more likely that the similarity in the combustion performance results occurred in these cases because the prevaporized liquid hydrocarbon fuel results are primarily limited by mixing constraints as opposed to kinetic limitations.

COMBUSTOR PERFORMANCE AT OTHER FLIGHT CONDITIONS

In addition to the combustor development tests performed at the simulated Mach 5.6 flight conditions, connected-pipe tests of selected combustor configurations were also conducted at higher and lower inlet air temperatures. Except for some early diagnostic tests that were performed at a Mach 3 combustor entrance condition, most of the connected-pipe tests at the higher inlet air temperatures were conducted using a Mach 3.7 facility nozzle to establish combustor entrance conditions that corresponded to a flight Mach number of 7. At the lower inlet air temperatures, all of the connected-pipe tests were conducted using the same Mach 3.0 facility nozzle that was used to simulate the Mach 5.6 flight conditions. Since the combustor entrance Mach number at lower flight speeds would likely be lower than 3.0, these tests provided a conservative simulation (from an ignition and combustion standpoint) of lower flight Mach numbers. That is, for a given inlet air stagnation temperature, the inlet air static temperature and velocity established in the test facility were somewhat lower and higher, respectively, than the corresponding values would actually be in flight. Combustor test data for the tests conducted at the various simulated flight conditions are included in the Appendix.

Combustor Performance at Mach 7 Flight Conditions

Additional connected-pipe tests were conducted at combustor entrance conditions simulating flight at Mach 7. The combustor entrance conditions for these tests were calculated on a vitiated air basis to match the static pressure, sensible enthalpy and velocity that would exist during flight in clean air; they comprised a combustor entrance Mach number of 3.7, a stagnation temperature of 3400 R and a stagnation pressure of 950 psia. The high-pressure facility air supply and the hydrogen-fueled vitiating air heater developed for the establishment of these conditions were found to operate stably and reliably. Tests were conducted in test sections having wall contours comprising initial/final wall divergence angles of 2-deg/2-deg and 2-deg/3-deg using a ramp-mounted pilot/primary fuel injector configuration as described previously. Primary fuel was injected through three 0.041-in. diameter orifices on the outside of the pilot cowl; secondary fuel was injected through a single row of three flush mounted 0.063-in. diameter orifices located on the lower wall of the test section approximately two inches downstream of the pilot exit station.

Previous tests of the ramp-mounted pilot configuration in a 2-deg/2-deg test section at combustor entrance conditions simulating flight at a Mach number of 5.6 (combustor entrance Mach number of 3.0, stagnation temperature of 2675 R and stagnation pressure of 200 psia) had shown that ethylene injected into the ramp-mounted pilot would autoignite and burn stably over a wide range of equivalence ratios without the need for an internal flameholder. Furthermore, when the ramp-mounted pilot was operated in conjunction with primary and secondary ethylene fuel injection, the pilot promoted efficient supersonic combustion of the injected fuel. At high mainstream equivalence ratios the heat release rates were sufficient to induce mode transition. For this configuration, combustor wall static pressure measurements made over a range of equivalence ratios during a Mach 5.6 test were presented previously in Fig. 9.

At the Mach 7 conditions, as at the lower flight Mach number conditions, the ramp-mounted, air-breathing pilot once again provided for autoignition of the pilot ethylene fuel without the need for an internal flameholder and also operated stably over a wide range of internal equivalence ratios. At the Mach 7 conditions, the pilot promoted the successful ignition and combustion of mainstream (primary and secondary) ethylene fuel. Combustor wall static pressure measurements made over a range of equivalence ratios during a Mach 7 test conducted in a 2-deg/2-deg test section are presented in Fig. 13. At the highest equivalence ratio established during this test (0.29), the maximum combustor pressure rise level achieved (4.6) is indicative that a high level of heat release was achieved within the 4-ft. long combustor.

In comparing the Mach 7 test results with those achieved at Mach 5.6 conditions in the same test configuration, it can be seen that at the same equivalence ratio, the combustor pressure rises achieved at the higher Mach number conditions are somewhat smaller than those experienced at the lower speed conditions. This result was expected and is a consequence of the higher inlet air enthalpy associated with the higher-speed conditions, i.e., the same absolute heat release level (resulting from combustion of fuel) will produce a smaller percentage change in the air enthalpy at the higher Mach number conditions and consequently a smaller combustor pressure rise. Similarly, although transition to a mixed supersonic/subsonic mode of operation was experienced at the Mach 5.6 conditions, somewhat higher levels of heat release would be required to produce the pressure disturbances needed to promote similar transition behavior at the Mach 7 conditions. Although such levels of heat release could readily be provided through the use of dual or multiple pilots, such tests were beyond the scope of the planned Mach 7 test series and were not conducted as part of this program.

The results achieved during the Mach 7 tests of the single ramp-mounted pilot configuration in which the combustor wall contour was set at a 2-deg/3-deg configuration were very similar to those achieved with the nominal 2-deg/2-deg wall contour except that the pressure rises experienced in the aft section of the varied were somewhat lower, as expected. In the 2-deg/3-deg combustor, a maximum combustor pressure rise of approximately 3.7 was achieved at the highest ethylene equivalence ratio established (0.30) during the tests.

Combustor Performance at Lower Inlet Air Temperatures

A limited series of combustor tests was conducted at vitiated air temperatures simulating flight at lower Mach numbers. These low temperature tests were conducted to determine the autoignition limits of the pilot with ethylene fuel and to evaluate the related combustor performance at the lower inlet air temperatures. Autoignition of ethylene injected into the pilot was achieved without the use of an internal flameholder at vitiated air temperatures as low as 2150 R. In a similar test conducted at a vitiated air temperature of 1950 R, the pilot ethylene did not autoignite. At the 2150 R test condition, the pilot operated stably over a wide range of internal equivalence ratios and promoted stable supersonic combustion of mainstream ethylene fuel injected through the baseline primary and secondary fuel injectors. At this test condition, the heat release rates achieved at an overall equivalence ratio of approximately 0.2 were sufficient to induce mode transition in the combustor. In the mixed (supersonic/subsonic) mode, conditions upstream of the air-breathing pilot remained unperturbed even in the presence of combustor pressure rises in excess of five to one. On the basis of the low-temperature test results, it was concluded that the pilot-stabilized supersonic combustor scheme can be implemented without the need for any auxiliary ignition aids at flight Mach numbers as low as approximately 4.5. For operation at lower flight Mach numbers, ignition and/or flameholding aids would be used to light the pilot.

SUMMARY AND RECOMMENDATIONS

Development of the UTRC air-breathing piloting concept has resulted in the establishment of a stable, efficient supersonic combustor capable of operation with a variety of hydrocarbon fuels over a wide range of flight conditions. Placement of the pilot on an inclined ramp within the combustor improved the pilot operation by desensitizing pilot performance to local boundary layer effects and eliminating the need for a bluff-body flameholder. At simulated Mach 5.6 and 7.0 flight conditions, a pilot-stabilized combustor using a single ramp-mounted pilot provided for the attainment of high combustor pressure ratios with gaseous ethylene fuel without generating any significant combustor/inlet interactions. At the Mach 5.6 flight condition, similar combustor performance characteristics were demonstrated with prevaporized JP-7 fuel. The results of limited tests at lower inlet air temperatures showed that the pilot-stabilized combustor could also operate successfully with ethylene fuel, without the need for any auxiliary ignition aids, at flight Mach numbers as low as approximately 4.5. With ignition and/or flameholding aids, the concept could be extended to even lower flight Mach numbers. Additional demonstration tests were also performed at the Mach 5.6 flight condition of a test configuration comprising dual ramp-mounted pilots and multiple fuel injectors in which heat release rates closer to those expected in an actual engine were established. During these tests, the combustor contour and the secondary fuel injection location were varied and operation at overall equivalence ratios as high as approximately 0.5 (with ethylene fuel) was achieved without experiencing significant inlet/combustor interactions. In an actual engine, careful matching of the combustor contour and the pilot, primary and secondary fuel injector locations will be required to ensure similar interaction-free operation at overall equivalence ratios approaching 1.0, the desired level for high-thrust operation.

The test activities described above have further established the effectiveness of the pilot-stabilized combustor concept and advanced the technology for continued development of a hydrocarbon-fueled scramjet engine. It is recommended that future activities be focussed on the connected-pipe development of an engine-scale combustor having a full complement of pilots and fuel injectors to more fully address the interactions between these components and the combustor geometry. These activities should include consideration of direct thrust measurements and calorimetry to aid in the evaluation of combustor performance.

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NOMENCLATURE

A	Cross-sectional Area
ΔA	Change in Combustor Area Between Two Axial Stations
h	Duct Height
L	Length
M	Mach Number
M_o	Flight Mach Number
P	Pressure
P_s	Static Pressure
P_{so}	Combustor Entrance Static Pressure
T	Temperature
T_f	Fuel Temperature
T_o	Stagnation Temperature
X	Axial Distance From Tunnel Nozzle Exit Station
X_{sec}	Secondary Fuel Injector Location
Φ	Weight Flow Rate Equivalence Ratio

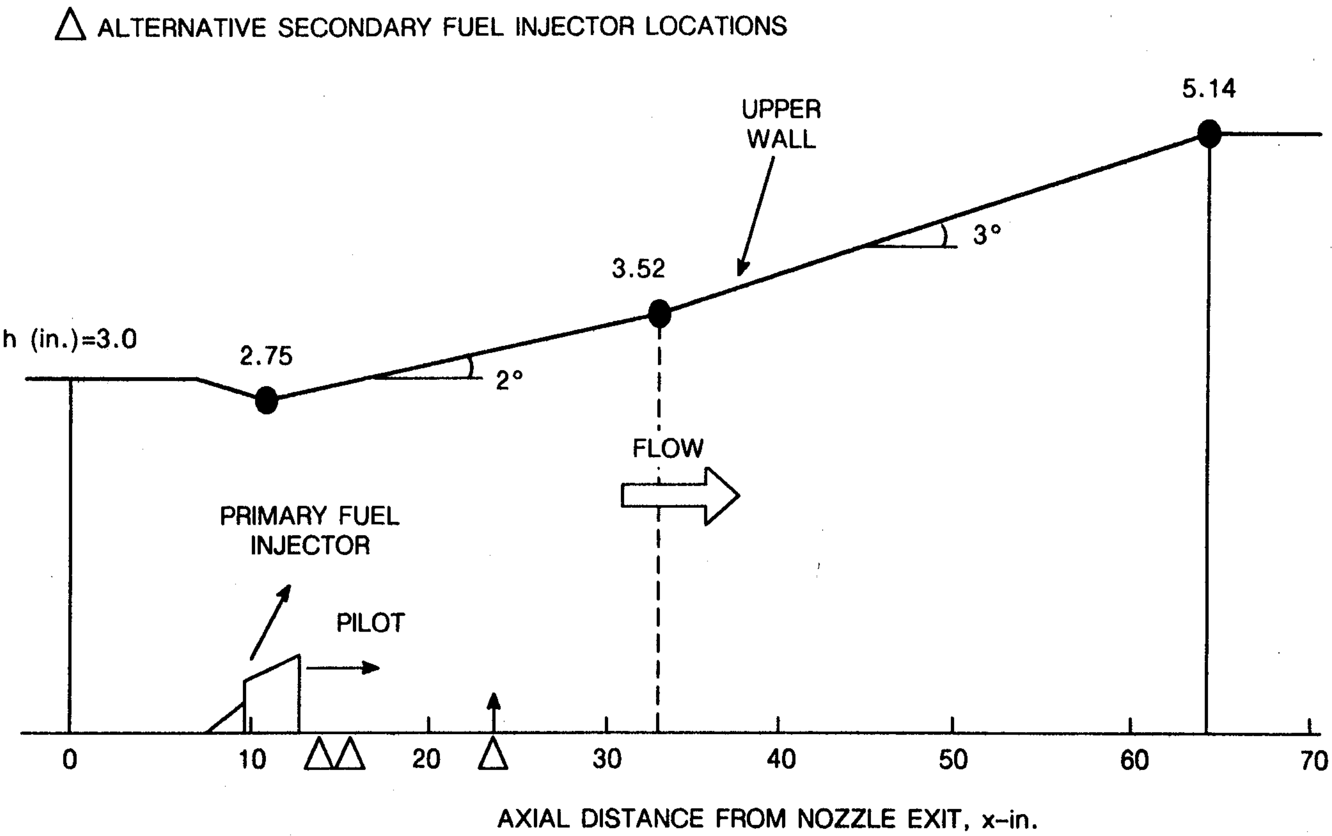

Fig. 1. Variable-Geometry Test Section Configuration

92-5-17-1

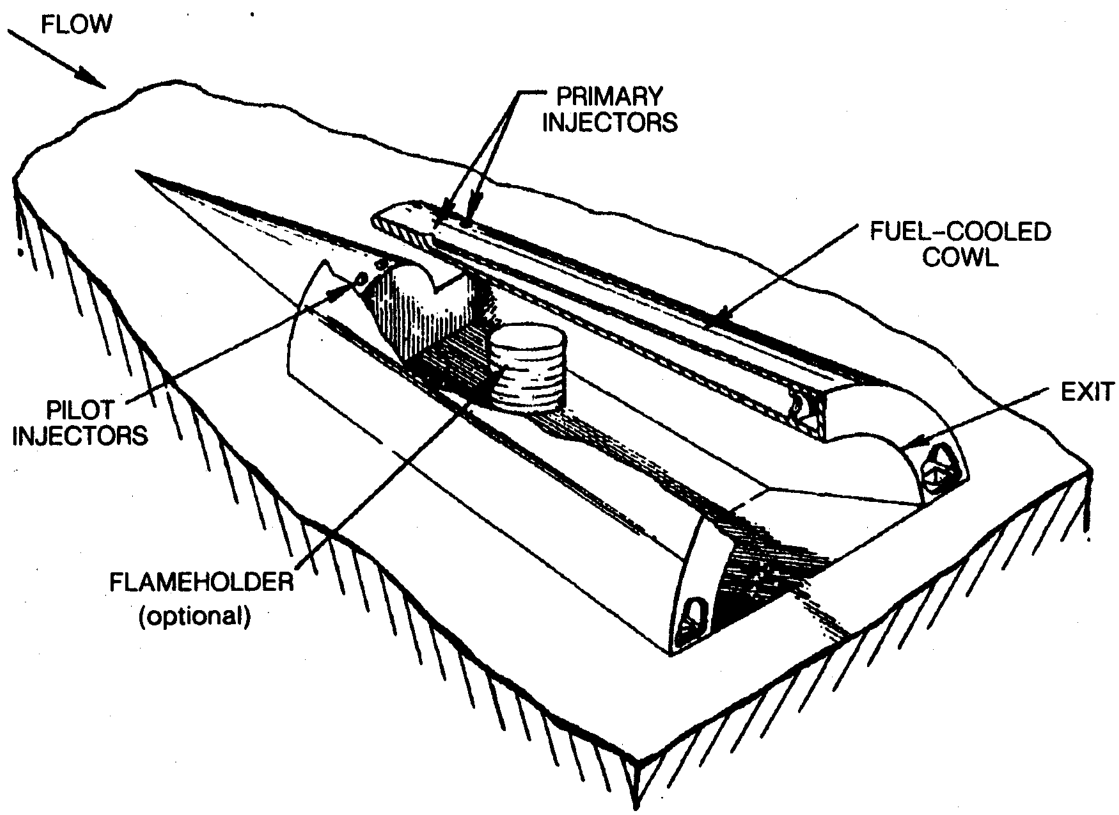

Fig. 2. Air-Breathing Pilot/Injector

92-5-17-2

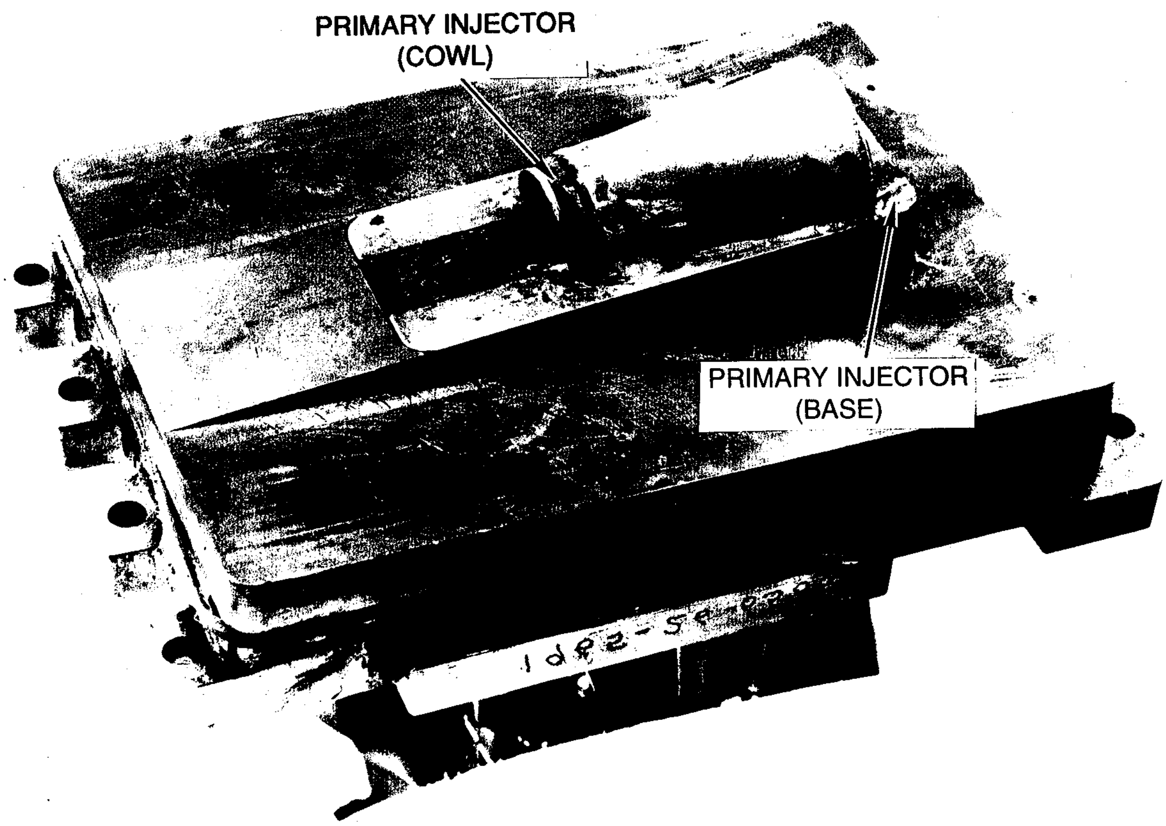

Fig. 3. Ramp-Mounted Pilot Installation

91-460-1

92-5-17-3

Fig. 4. Dual Ramp-Mounted Pilot Installation

92-039 #9

92-5-17-4

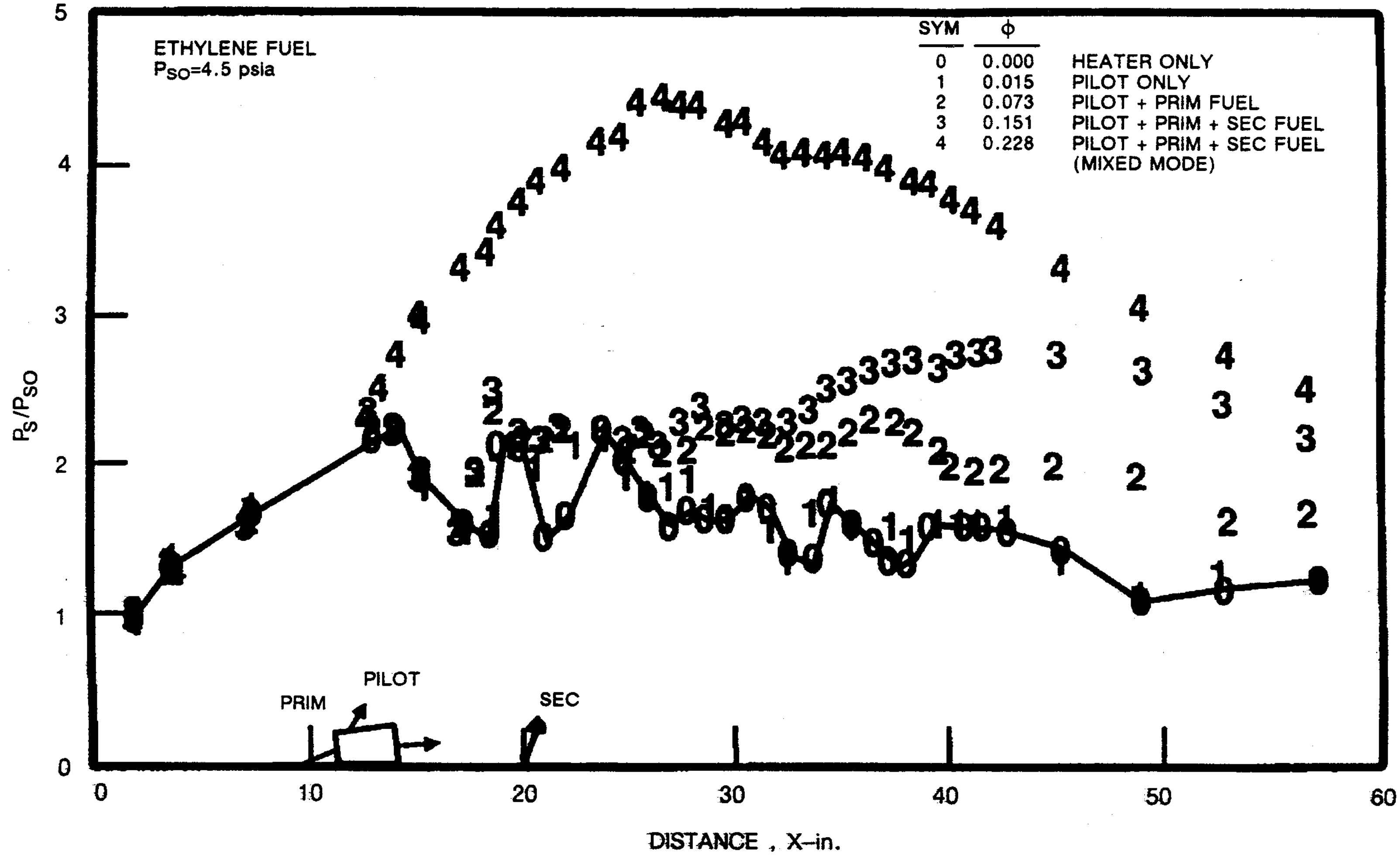

Fig. 5. Lower-Wall Axial Pressure Distributions on Centerline

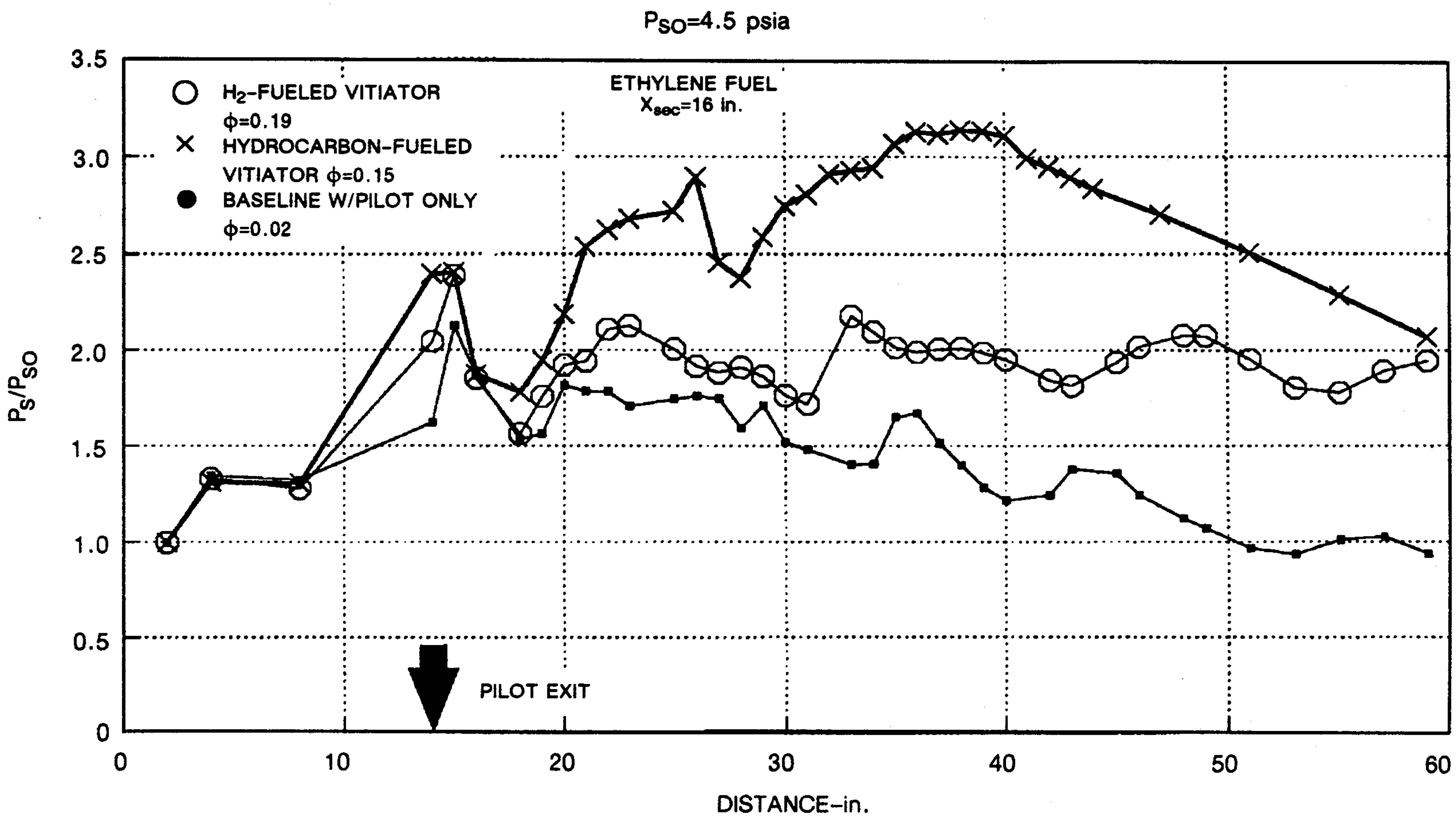

Fig. 6. Effect of Vitiation Heater on Combustor Performance

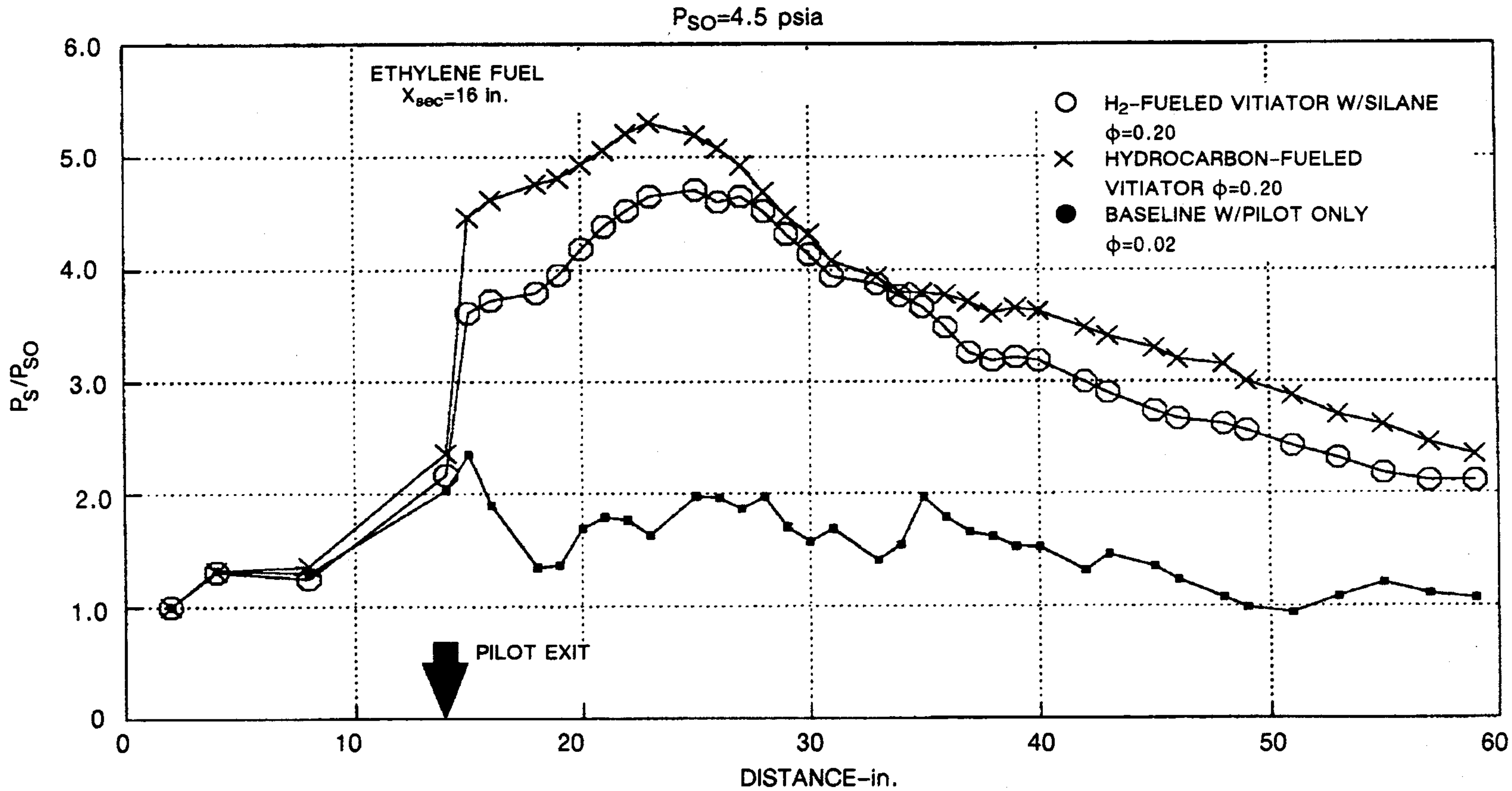

Fig. 7. Effect of Silane on Combustor Performance

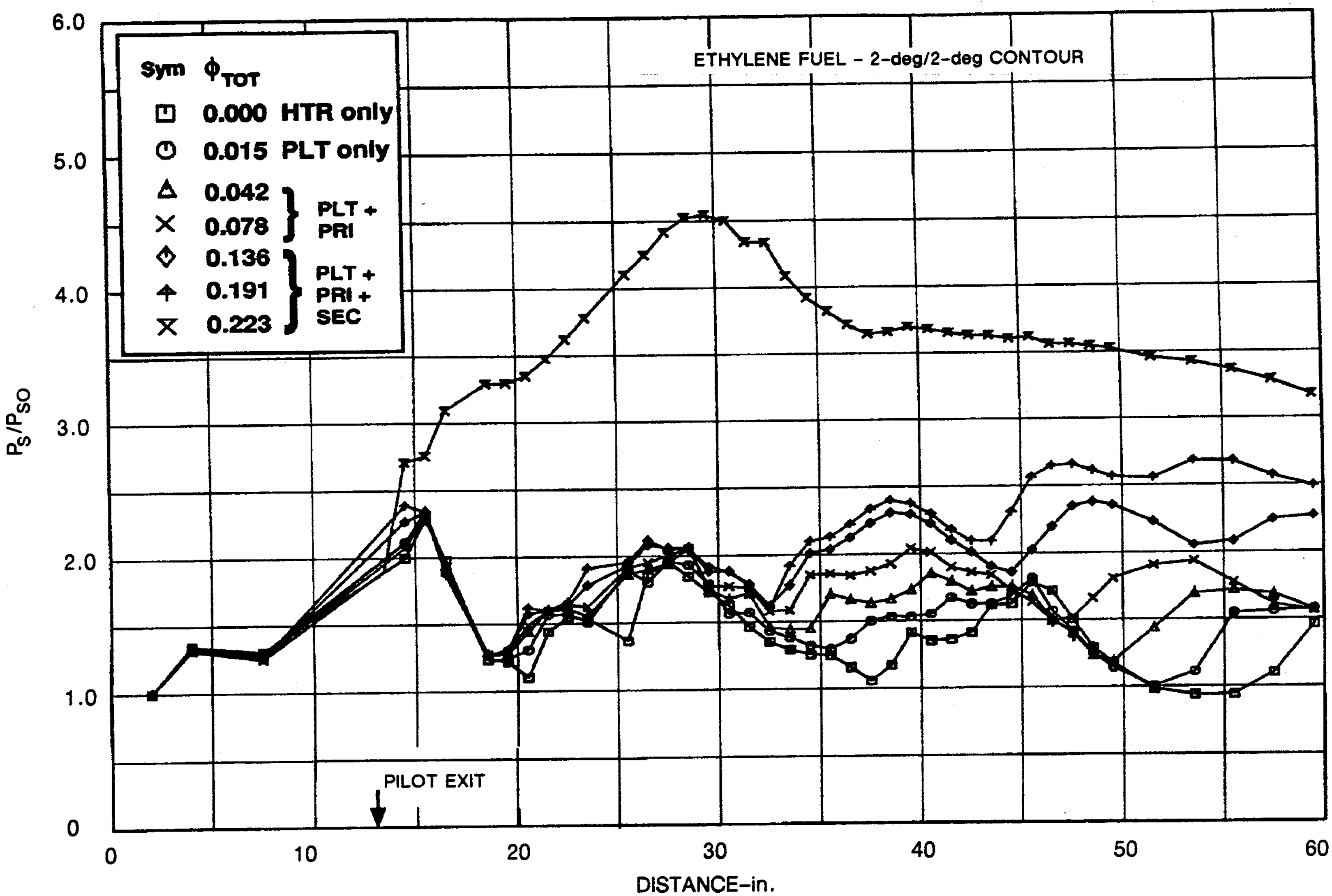

Fig. 8. Combustor Performance with Flush-Mounted Pilot

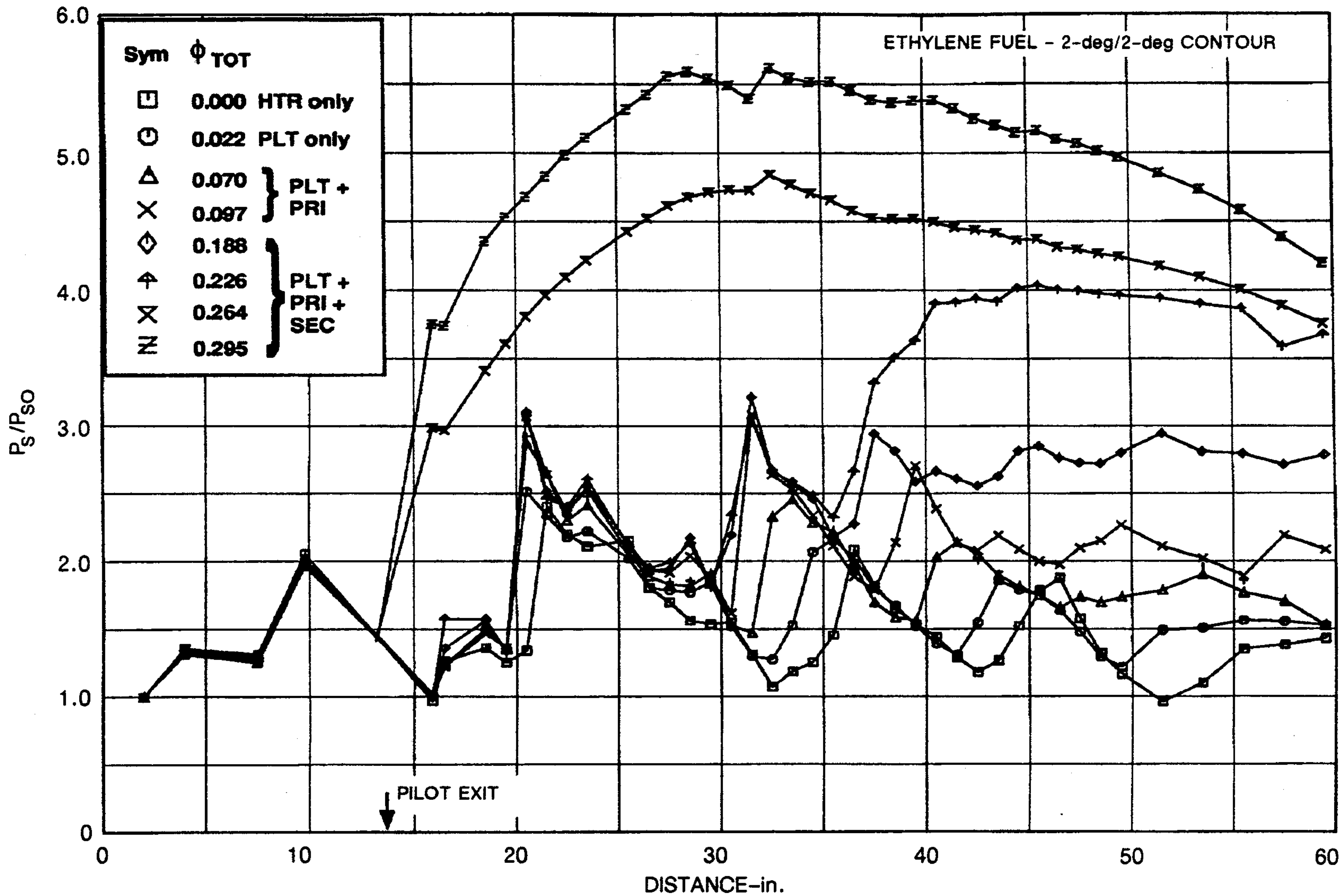

Fig. 9. Combustor Performance with Ramp-Mounted Pilot

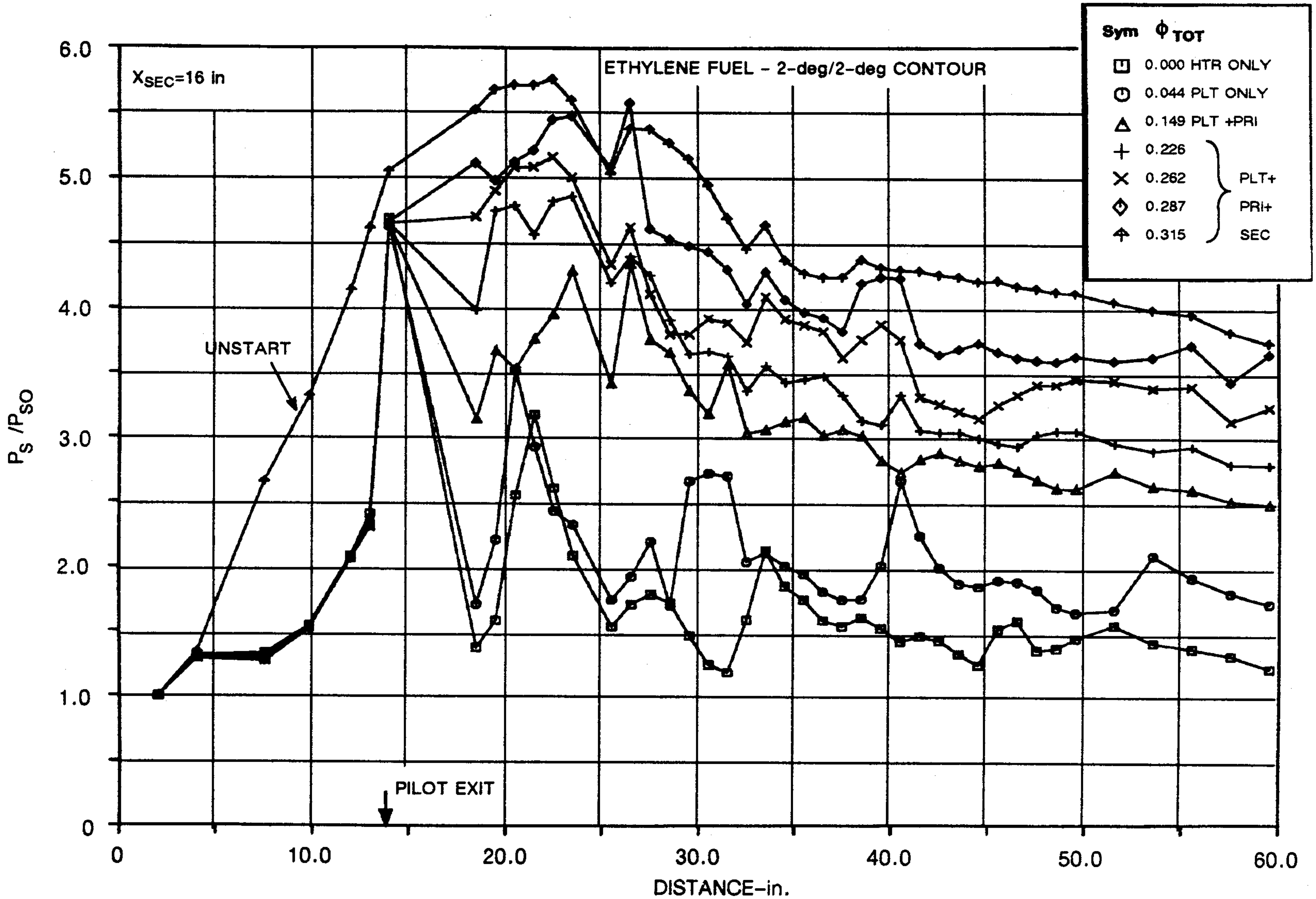

Fig. 10. Combustor Performance with Dual Ramp-Mounted Pilots

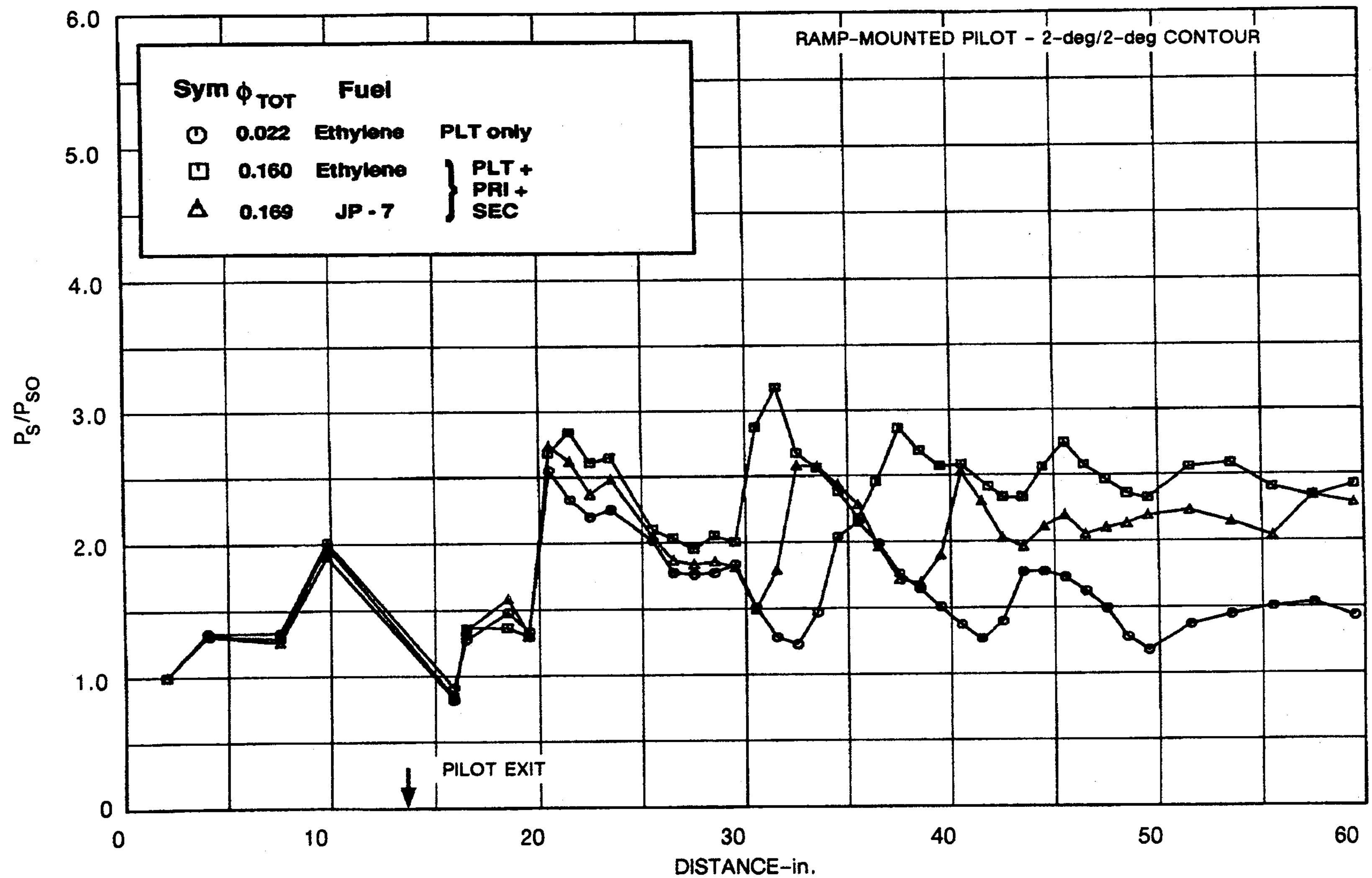

Fig. 11. Effect of Fuel Type on Combustor Performance

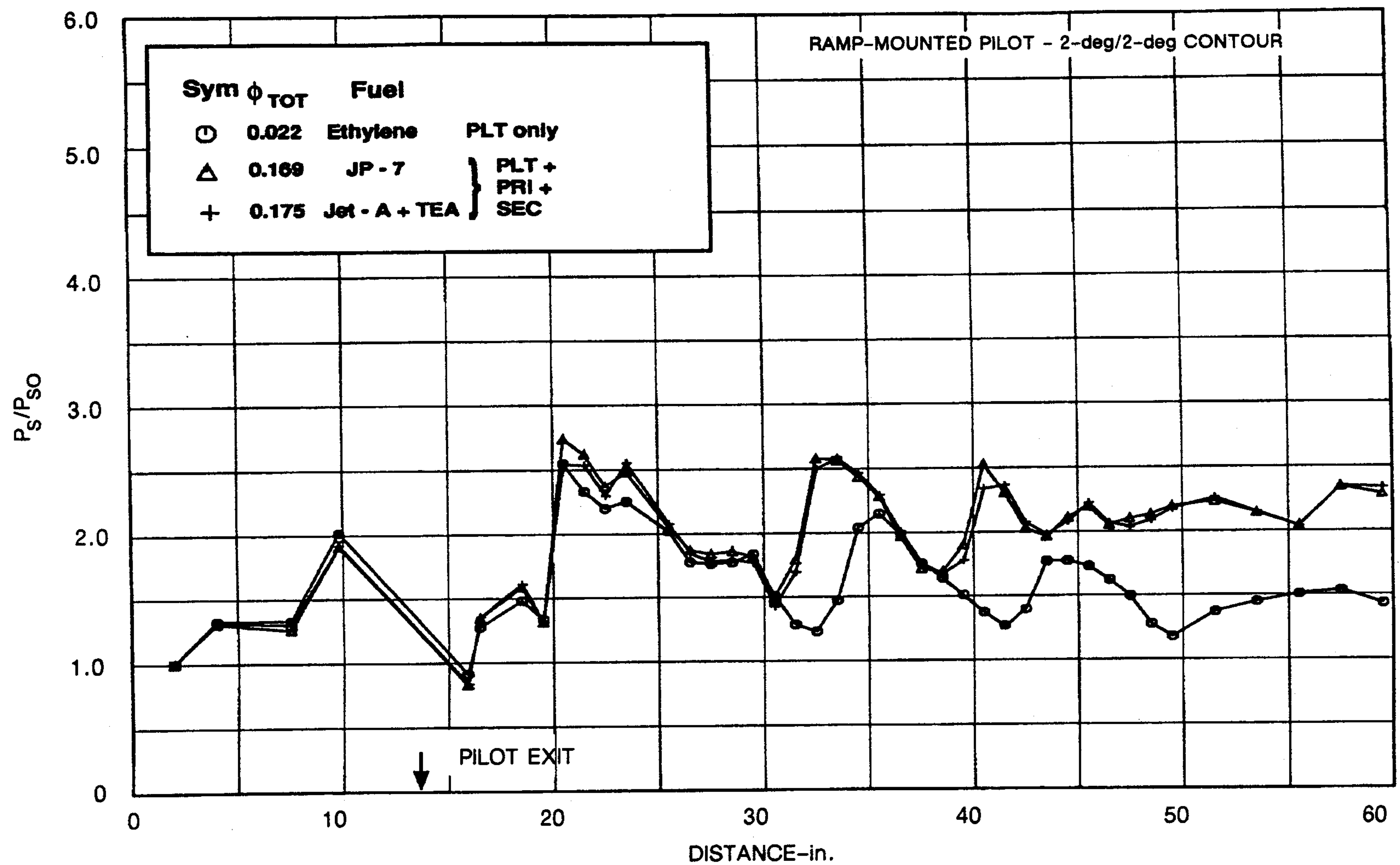

Fig. 12. Effect of Fuel Additive on Combustor Performance

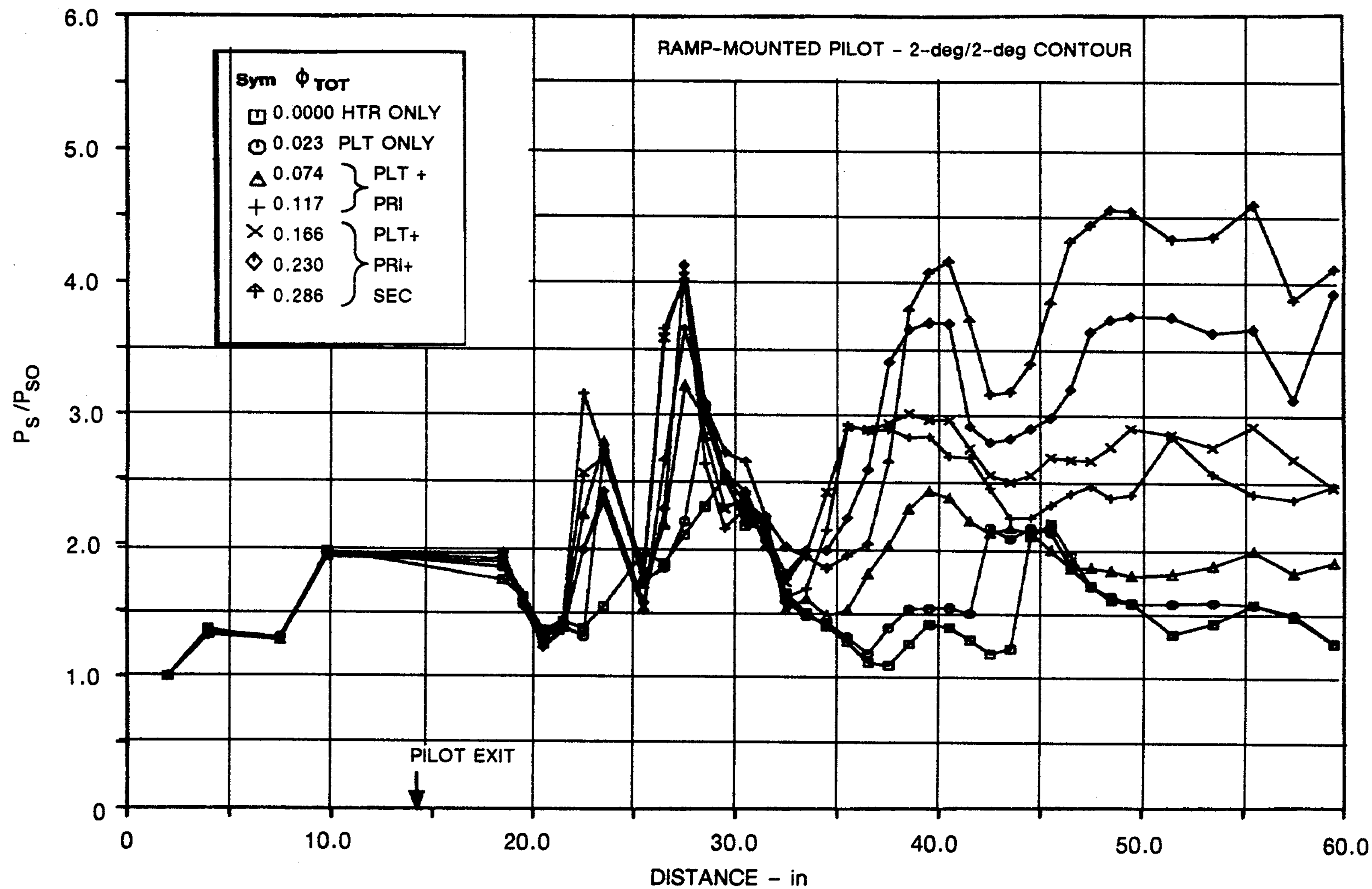

Fig. 13. Combustor Performance at Simulated Mach 7 Flight Conditions

APPENDIX – COMBUSTOR TEST SUMMARY

This appendix comprises a data summary for the combustor tests performed under the extension to Phase II of the test program. The run numbers are chronological and start with those tests in which the combustor fuel was doped with silane to reproduce the combustor results previously measured during the earlier part of the Phase II test program using the hydrocarbon-fueled vitiating air heater. All results presented herein were achieved using a hydrogen-fueled vitiating air heater. For each tabulated run, data are presented for a number of "bursts" corresponding to different fuel equivalence ratios. Each "burst" represents a different two-second period of time during which steady-state test conditions were established and over which the recorded data were averaged. The data presented for each test include descriptions of the simulated flight Mach number, the combustor wall contour, the pilot configuration and the test fuel, calculated values of the fuel equivalence ratios (pilot, primary, secondary and total), calculated wall static pressure-area integrals for the upstream and downstream straight portions of the test section (based on measured wall static pressures) and values of the overall combustor pressure-area integral normalized to a no-fuel condition.

The nominal combustor entrance conditions corresponding to the two flight Mach numbers simulated during the test program are presented below:

Flight Mach number	5.6	7.0
Combustor entrance Mach number	3.0	3.7
Combustor entrance stagnation temperature (R)	2675	3400
Combustor entrance static temperature (R)	1035	1145
Combustor entrance stagnation pressure (psia)	200	950
Combustor entrance static pressure (psia)	4.5	6.0
Combustor entrance vitiated airflow rate (lb/sec)	8.0	12.0

APPENDIX - COMBUSTOR TEST SUMMARY

RUN	M_o	CONTOUR up/dwn	FUEL	BURST	EQUIVALENCE RATIO pilot	primary	secondary	total	$\int PdA/(P_{so}*\Delta A)$ upstream	dwnstrm	NORMALIZED $\int PdA/(Pso*\Delta A)$	COMMENTS
260	5.6	2-deg/3-deg	ETHYLENE	12	0.0000	0.0000	0.0000	0.0000	1.678	1.146	0.000	Silane added to
		Flush-Mounted	+	18	0.0143	0.0028	0.0000	0.0171	1.757	1.243	0.062	Pilot & Primary
		Pilot	SILANE/H2	23	0.0142	0.0668	0.0000	0.0810	1.872	1.476	0.219	Fuel Only
				25	0.0142	0.0683	0.0000	0.0825	1.876	1.498	0.241	SAME SEC INJ
				28	0.0143	0.0695	0.1288	0.2126	2.015	2.061	0.575	THRU RUN 278
				32	0.0143	0.0698	0.1570	0.2411	4.286	2.791	1.473	X_{sec}=14 in
				39	0.0143	0.0702	0.1519	0.2364	4.242	2.778	1.460	(Two 0.062-in holes)
261	5.6	2-deg/3-deg	ETHYLENE	15	0.0000	0.0000	0.0000	0.0000	1.675	1.153	0.000	Silane added to
		Flush-Mounted	+	20	0.0144	0.0036	0.0000	0.0180	1.774	1.261	0.078	Pilot & Primary
		Pilot	SILANE/H2	26	0.0144	0.0344	0.0000	0.0488	1.833	1.343	0.127	Fuel Only
				28	0.0145	0.0531	0.0000	0.0676	1.873	1.429	0.190	
				30	0.0145	0.0713	0.0000	0.0858	1.911	1.509	0.253	
				32	0.0145	0.0919	0.0000	0.1064	1.937	1.627	0.330	
				36	0.0145	0.0920	0.0487	0.1552	1.990	1.864	0.486	
				38	0.0145	0.0920	0.0812	0.1877	2.040	2.059	0.616	
				40	0.0145	0.0919	0.1104	0.2168	2.044	2.248	0.734	
				43	0.0145	0.0919	0.1406	0.2470	4.266	2.770	1.485	
				47	0.0145	0.0918	0.1174	0.2237	4.106	2.651	1.365	
				50	0.0145	0.0915	0.0964	0.2024	3.498	2.558	1.148	
264	5.6	1-deg/4-deg	ETHYLENE	13	0.0000	0.0000	0.0000	0.0000	1.709	1.206	0.000	Silane added to
		Flush-Mounted	+	19	0.0146	0.0036	0.0000	0.0182	1.759	1.246	0.033	Pilot & Primary
		Pilot	SILANE/H2	25	0.0148	0.0706	0.0000	0.0854	1.988	1.539	0.272	Fuel Only
				31	0.0148	0.0702	0.1267	0.2117	4.022	2.549	1.180	
				40	0.0112	0.0649	0.1270	0.2031	4.083	2.571	1.194	Silane Off
265	5.6	1-deg/4-deg	ETHYLENE	13	0.0000	0.0000	0.0000	0.0000	1.733	1.216	0.000	Silane added to
		Flush-Mounted	+	18	0.0154	0.0000	0.0000	0.0154	1.785	1.298	0.050	Primary Fuel Only
		Pilot	SILANE/H2	24	0.0153	0.0611	0.0000	0.0764	1.935	1.574	0.280	
				29	0.0152	0.0633	0.0000	0.0785	1.949	1.592	0.291	Silane On
				38	0.0151	0.0619	0.1297	0.2067	4.294	2.659	1.262	
				40	0.0151	0.0587	0.1292	0.2030	4.264	2.653	1.255	Silane Off
266	5.6	1-deg/4-deg	ETHYLENE	13	0.0000	0.0000	0.0000	0.0000	1.727	1.215	0.000	Silane added to
	**	Flush-Mounted	+	21	0.0151	0.0000	0.0000	0.0151	1.754	1.281	0.040	Primary Fuel Only
		Pilot	SILANE/H2	26	0.0149	0.0622	0.0000	0.0771	1.897	1.512	0.225	** T_o=3000 R
				30	0.0148	0.0696	0.0000	0.0844	1.939	1.532	0.250	Silane On
				36	0.0148	0.0680	0.1495	0.2323	2.129	2.398	0.893	
				40	0.0147	0.0677	0.1347	0.2171	3.592	2.474	1.050	
267	5.6	1-deg/4-deg	ETHYLENE	10	0.0000	0.0000	0.0000	0.0000	1.751	1.236	0.000	
		Flush-Mounted	(HEATED)	20	0.0158	0.0000	0.0000	0.0158	1.754	1.283	0.027	Pilot Fuel Not Heated
		Pilot		25	0.0156	0.0509	0.0837	0.1502	2.039	1.934	0.512	T_f = 578 R
				30	0.0154	0.0477	0.0782	0.1413	2.029	1.972	0.545	T_f = 570 R
				32	0.0153	0.0475	0.0785	0.1413	2.021	1.964	0.539	T_f = 575 R
				34	0.0153	0.0469	0.0792	0.1414	2.011	1.938	0.520	T_f = 632 R
				36	0.0153	0.0456	0.0780	0.1389	2.004	1.916	0.502	T_f = 704 R
				38	0.0152	0.0443	0.0763	0.1358	1.996	1.900	0.489	T_f = 748 R
				40	0.0152	0.0433	0.0747	0.1332	1.990	1.890	0.482	T_f = 778 R
268	5.6	1-deg/4-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	1.735	1.221	0.000	
		Flush-Mounted	(HEATED)	16	0.0161	0.0000	0.0000	0.0161	1.788	1.310	0.051	Pilot Fuel Not Heated
		Pilot		20	0.0159	0.0464	0.0771	0.1394	2.052	1.923	0.517	T_f = 555 R
				23	0.0158	0.0454	0.0760	0.1372	2.029	1.920	0.518	T_f = 567 R
				25	0.0158	0.0444	0.0761	0.1363	2.014	1.894	0.497	T_f = 632 R
				28	0.0157	0.0423	0.0736	0.1316	2.001	1.878	0.482	T_f = 726 R
				32	0.0156	0.0400	0.0703	0.1259	1.993	1.883	0.482	T_f = 797 R
269	5.6	1-deg/4-deg	ETHYLENE	12	0.0000	0.0000	0.0000	0.0000	1.781	1.262	0.000	
		Flush-Mounted	(HEATED)	19	0.0153	0.0000	0.0000	0.0153	1.826	1.350	0.055	Pilot Fuel Not Heated
		Pilot		25	0.0152	0.0604	0.0931	0.1687	2.086	2.068	0.612	T_f = 1000 R
				38	0.0151	0.0574	0.0886	0.1611	3.263	2.325	0.882	T_f = 1086 R
270	5.6	2-deg/3-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	1.699	1.116	0.000	
		Flush-Mounted	(HEATED)	16	0.0156	0.0000	0.0000	0.0156	1.708	1.173	0.027	Pilot Fuel Not Heated
		Pilot		20	0.0154	0.0519	0.0798	0.1471	1.877	1.706	0.367	T_f = 1209 R
				24	0.0153	0.0536	0.0825	0.1514	1.885	1.761	0.403	T_f = 1136 R
				27	0.0152	0.0523	0.0806	0.1481	1.877	1.741	0.388	T_f = 1185 R
				30	0.0151	0.0502	0.0775	0.1428	1.877	1.732	0.382	T_f = 1295 R
				36	0.0150	0.0490	0.0754	0.1394	1.879	1.717	0.374	T_f = 1400 R
271	5.6	2-deg/3-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	1.705	1.119	0.000	
		Flush-Mounted	(HEATED)	16	0.0157	0.0000	0.0000	0.0157	1.718	1.175	0.029	Pilot Fuel Not Heated
		Pilot		19	0.0156	0.0865	0.1314	0.2335	1.952	1.929	0.510	T_f = 1122 R
				20	0.0156	0.0865	0.1315	0.2336	1.949	1.958	0.536	T_f = 1019 R
				21	0.0155	0.0866	0.1316	0.2337	1.953	1.962	0.540	T_f = 1065 R
				22	0.0155	0.0862	0.1311	0.2328	1.959	1.953	0.536	T_f = 1175 R
				25	0.0155	0.0859	0.1306	0.2320	1.955	1.939	0.524	T_f = 1295 R

APPENDIX - COMBUSTOR TEST SUMMARY

RUN	M_∞	CONTOUR up/dwn	FUEL	BURST	EQUIVALENCE RATIO PILOT	PRIMARY	SECONDARY	TOTAL	$\int PdA/(P_\infty * \Delta A)$ upstream	dwnstrm	NORMALIZED $\int PdA/(P_\infty * \Delta A)$	COMMENTS
272	5.6	2-deg/3-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	1.639	1.077	0.000	Silane added to
		Flush-Mounted	+	17	0.0154	0.0000	0.0000	0.0154	1.675	1.143	0.036	Primary Fuel Only
		Pilot	SILANE/H2	22	0.0152	0.0531	0.0000	0.0683	1.764	1.375	0.167	Silane Off
				25	0.0151	0.0597	0.0000	0.0748	1.789	1.397	0.183	Silane On
				29	0.0151	0.0605	0.0680	0.1436	1.867	1.612	0.319	
				40	0.0151	0.0603	0.1582	0.2336	1.968	2.146	0.696	
				43	0.0151	0.0606	0.1664	0.2421	2.014	2.797	1.105	
273	5.6	2-deg/3-deg	ETHYLENE	14	0.0000	0.0000	0.0000	0.0000	1.625	1.070	0.000	Silane added to
		Flush-Mounted	+	20	0.0147	0.0039	0.0000	0.0186	1.695	1.149	0.054	Pilot & Primary
		Pilot	SILANE/H2	26	0.0147	0.0643	0.0000	0.0790	1.799	1.393	0.191	Fuel Only
				35	0.0146	0.0650	0.1537	0.2333	2.021	2.153	0.747	
				41	0.0146	0.0648	0.1578	0.2372	2.050	2.216	0.781	
				47	0.0146	0.0622	0.1649	0.2417	1.969	2.051	0.654	
274	5.6	1-deg/4-deg	ETHYLENE	12	0.0000	0.0000	0.0000	0.0000	1.801	1.299	0.000	
		Flush-Mounted	(HEATED)	18	0.0143	0.0000	0.0000	0.0143	1.874	1.397	0.086	Pilot Fuel Not Heated
		Pilot		22	0.0144	0.0773	0.1170	0.2087	4.663	2.561	1.140	T_f = 1024 R
				24	0.0144	0.0745	0.1128	0.2017	4.325	2.532	1.094	T_f = 1100 R
				27	0.0144	0.0683	0.1035	0.1862	4.099	2.454	1.020	T_f = 1318 R
				30	0.0144	0.0647	0.0979	0.1770	3.951	2.423	0.983	T_f = 1453 R
				33	0.0144	0.0606	0.0919	0.1669	3.712	2.370	0.912	T_f = 1612 R
275	5.6	1-deg/4-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	1.795	1.240	0.000	
		Flush-Mounted	(HEATED)	17	0.0150	0.0000	0.0000	0.0150	1.835	1.339	0.058	Pilot Fuel Not Heated
		Pilot		20	0.0150	0.0439	0.0669	0.1258	2.032	1.804	0.419	T_f = 1237 R
				22	0.0150	0.0440	0.0671	0.1261	2.028	1.820	0.435	T_f = 1244 R
				26	0.0150	0.0413	0.0629	0.1192	1.998	1.789	0.409	T_f = 1429 R
276	5.6	1-deg/4-deg	ETHYLENE	16	0.0000	0.0000	0.0000	0.0000	1.727	1.206	0.000	
		Flush-Mounted		33	0.0146	0.0000	0.0000	0.0146	1.793	1.319	0.063	
		Pilot		39	0.0144	0.0575	0.0000	0.0719	1.948	1.576	0.283	
				41	0.0144	0.0590	0.0362	0.1096	2.008	1.731	0.397	
				44	0.0143	0.0592	0.1033	0.1768	2.119	2.214	0.768	
				45	0.0143	0.0592	0.1229	0.1964	2.290	2.373	0.892	
				47	0.0142	0.0592	0.1361	0.2095	4.675	2.707	1.341	Mode Transition
277	5.6	2-deg/2-deg	ETHYLENE	12	0.0000	0.0000	0.0000	0.0000	1.629	1.295	0.000	
		Flush-Mounted		17	0.0154	0.0000	0.0000	0.0154	1.705	1.427	0.057	
		Pilot		21	0.0153	0.0262	0.0000	0.0415	1.748	1.562	0.127	
				23	0.0153	0.0437	0.0000	0.0590	1.762	1.637	0.170	
				27	0.0153	0.0622	0.0000	0.0775	1.777	1.767	0.231	
				31	0.0153	0.0629	0.0579	0.1361	1.834	2.139	0.388	
				33	0.0153	0.0631	0.1227	0.2011	1.860	2.436	0.533	
				37	0.0153	0.0631	0.1445	0.2229	3.748	3.482	1.498	Mode Transition
278	5.6	2-deg/2-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	1.705	1.342	0.000	
		Flush-Mounted	(HEATED)	17	0.0151	0.0000	0.0000	0.0151	1.732	1.450	0.037	Pilot Fuel Not Heated
		Pilot		21	0.0151	0.0583	0.0891	0.1625	1.882	2.314	0.459	T_f = 1154 R
				25	0.0150	0.0582	0.0890	0.1622	1.873	2.298	0.450	T_f = 1184 R
				29	0.0150	0.0565	0.0864	0.1579	1.860	2.279	0.435	T_f = 1313 R
				34	0.0150	0.0535	0.0818	0.1503	1.840	2.188	0.388	T_f = 1474 R
279	5.6	2-deg/2-deg	ETHYLENE	12	0.0000	0.0000	0.0000	0.0000	0.791	0.683	0.000	SAME SEC INJ
		Ramp-Mounted		19	0.0122	0.0000	0.0000	0.0122	0.817	0.731	0.058	THRU RUN 294
		Pilot		21	0.0142	0.0000	0.0000	0.0142	0.821	0.738	0.073	X_{sec}= 16 in
				25	0.0163	0.0000	0.0000	0.0163	0.824	0.744	0.087	(Two 0.062-in holes)
				30	0.0185	0.0000	0.0000	0.0185	0.834	0.758	0.107	
				34	0.0227	0.0000	0.0000	0.0227	0.849	0.777	0.133	Pilot Performance Only
				37	0.0255	0.0000	0.0000	0.0255	0.860	0.794	0.156	
				40	0.0284	0.0000	0.0000	0.0284	0.877	0.828	0.197	
				44	0.0292	0.0000	0.0000	0.0292	0.882	0.839	0.209	
				48	0.0186	0.0000	0.0000	0.0186	0.848	0.783	0.144	
280	5.6	2-deg/2-deg	ETHYLENE	12	0.0000	0.0000	0.0000	0.0000	0.782	0.678	0.000	
		Ramp-Mounted		18	0.0215	0.0000	0.0000	0.0215	0.849	0.766	0.124	
		Pilot		23	0.0215	0.0444	0.0000	0.0659	0.934	0.903	0.295	
				25	0.0215	0.0604	0.0000	0.0819	0.962	0.957	0.371	
				27	0.0215	0.0751	0.0000	0.0966	0.997	1.020	0.460	
				30	0.0214	0.0747	0.0519	0.1480	1.027	1.170	0.619	
				33	0.0214	0.0743	0.1090	0.2047	1.053	1.421	0.870	
				36	0.0214	0.0742	0.1352	0.2308	1.061	1.634	1.067	
281	5.6	2-deg/2-deg	ETHYLENE	10	0.0000	0.0000	0.0000	0.0000	0.787	0.683	0.000	
		Ramp-Mounted		16	0.0216	0.0000	0.0000	0.0216	0.857	0.772	0.125	
		Pilot		18	0.0217	0.0482	0.0000	0.0699	0.933	0.887	0.266	
				19	0.0214	0.0658	0.0000	0.0872	0.959	0.954	0.348	
				23	0.0214	0.0751	0.0000	0.0965	1.014	1.045	0.491	
				26	0.0214	0.0752	0.0909	0.1875	1.058	1.353	0.795	
				28	0.0214	0.0750	0.1297	0.2261	1.079	1.825	1.233	
				31	0.0215	0.0752	0.1676	0.2643	2.075	2.125	1.954	Mode Transition
				33	0.0215	0.0751	0.1985	0.2951	2.513	2.474	2.470	Mode Transition

APPENDIX - COMBUSTOR TEST SUMMARY

RUN	M_0	CONTOUR up/dwn	FUEL	BURST	EQUIVALENCE RATIO PILOT	PRIMARY	SECONDARY	TOTAL	$\int PdA/(P_{\infty}*\Delta A)$ upstream	dwnstrm	NORMALIZED $\int PdA/(P_{\infty}*\Delta A)$	COMMENTS
282	5.6	2-deg/2-deg	ETHYLENE	15	0.0000	0.0000	0.0000	0.0000	0.803	0.687	0.000	MODIFIED PRIM INJ
		Ramp-Mounted		20	0.0236	0.0000	0.0000	0.0236	0.866	0.767	0.113	(Five 0.041-in holes)
		Pilot		22	0.0236	0.0367	0.0000	0.0603	0.938	0.864	0.240	(Wcowl/Wbase = 1.5)
				26	0.0234	0.1273	0.0000	0.1507	1.053	1.218	0.611	
				27	0.0233	0.1518	0.0000	0.1751	1.025	1.367	0.690	
				28	0.0233	0.1675	0.0000	0.1908	0.929	1.468	0.771	
				31	0.0231	0.1296	0.0491	0.2018	1.077	1.419	0.824	
				33	0.0231	0.1290	0.1037	0.2558	1.097	1.827	1.184	
				35	0.0230	0.1288	0.1443	0.2961	1.766	2.237	1.889	Mode Transition
283	5.6	2-deg/2-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	0.802	0.677	0.000	MODIFIED PRIM INJ
		Ramp-Mounted		16	0.0217	0.0000	0.0000	0.0217	0.857	0.754	0.108	(Five 0.041-in holes)
		Pilot		18	0.0216	0.0400	0.0000	0.0616	0.940	0.864	0.254	(Wcowl/Wbase = 1.5)
				20	0.0214	0.0886	0.0000	0.1100	1.015	0.999	0.438	
				23	0.0214	0.1321	0.0000	0.1535	0.987	0.952	0.360	
				26	0.0213	0.1308	0.0795	0.2316	1.062	1.479	0.891	
				28	0.0213	0.1305	0.1196	0.2714	1.075	1.846	1.233	
				31	0.0213	0.1306	0.1569	0.3088	1.976	1.993	1.762	Mode Transition
				32	0.0213	0.1306	0.1487	0.3006	1.949	1.964	1.730	Mode Transition
284	5.6	2-deg/2-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	0.798	0.678	0.000	SEC INJ="base" holes
		Ramp-Mounted		16	0.0225	0.0000	0.0000	0.0225	0.858	0.754	0.110	for this run only
		Pilot		18	0.0223	0.0320	0.0000	0.0543	0.907	0.822	0.203	
				20	0.0222	0.0592	0.0000	0.0814	0.966	0.924	0.330	
				22	0.0222	0.0842	0.0000	0.1064	1.038	1.057	0.527	
				24	0.0221	0.0846	0.0117	0.1184	1.056	1.101	0.577	
				26	0.0220	0.0839	0.0378	0.1437	1.068	1.169	0.631	
				28	0.0219	0.0833	0.0551	0.1603	1.079	1.240	0.699	
				29	0.0218	0.0831	0.0721	0.1770	1.075	1.315	0.738	
				32	0.0218	0.0827	0.0822	0.1867	1.043	1.419	0.804	
				35	0.0217	0.0613	0.0801	0.1631	1.071	1.324	0.749	
287	5.6	2-deg/2-deg	JP-7	10	0.0000	0.0000	0.0000	0.0000	0.825	0.693	0.000	Pilot Fuel= Ethylene
		Ramp-Mounted	(HEATED)	17	0.0222	0.0000	0.0000	0.0222	0.880	0.781	0.121	(not heated)
		Pilot		22	0.0220	0.0547	0.0832	0.1599	0.904	0.820	0.170	T_f = 1110 R
				27	0.0219	0.0536	0.0815	0.1570	0.995	1.047	0.421	T_f = 816 R
				33	0.0217	0.0495	0.0753	0.1465	1.010	1.117	0.495	T_f = 1123 R
				36	0.0217	0.0399	0.0607	0.1223	1.002	1.083	0.459	T_f = 1317 R
				39	0.0216	0.0342	0.0520	0.1078	0.963	0.998	0.358	T_f = 1534 R
288	5.6	2-deg/2-deg	JP-7	12	0.0000	0.0000	0.0000	0.0000	0.816	0.703	0.000	Pilot Fuel= Ethylene
		Ramp-Mounted	(HEATED)	18	0.0220	0.0000	0.0000	0.0220	0.886	0.788	0.129	(not heated)
		Pilot		24	0.0218	0.0683	0.1038	0.1939	1.006	1.109	0.473	T_f = 1632 R
				29	0.0217	0.0675	0.1025	0.1917	1.025	1.181	0.553	T_f = 1186 R
				31	0.0217	0.0615	0.0934	0.1766	1.028	1.187	0.561	T_f = 1287 R
				35	0.0216	0.0587	0.0891	0.1694	1.011	1.120	0.493	T_f = 1431 R
				41	0.0215	0.0590	0.0896	0.1701	1.015	1.132	0.507	T_f = 1405 R
289	5.6	2-deg/2-deg	JP-7	13	0.0000	0.0000	0.0000	0.0000	0.837	0.734	0.000	Pilot Fuel= Ethylene
		Ramp-Mounted	(HEATED)	17	0.0221	0.0000	0.0000	0.0221	0.887	0.789	0.088	(not heated)
		Pilot		25	0.0217	0.0958	0.1456	0.2631	1.006	1.175	0.472	T_f = 774 R
				37	0.0214	0.0960	0.1459	0.2633	1.006	1.203	0.498	T_f = 774 R
290	5.6	2-deg/2-deg	JP-7	12	0.0000	0.0000	0.0000	0.0000	0.816	0.698	0.000	Pilot Fuel= Ethylene
		Ramp-Mounted	(HEATED)	17	0.0225	0.0000	0.0000	0.0225	0.883	0.788	0.126	(not heated)
		Pilot		29	0.0221	0.0624	0.0948	0.1793	1.002	1.103	0.471	T_f = 1534 R
				41	0.0220	0.0651	0.0989	0.1860	1.011	1.138	0.511	T_f = 1464 R
291	5.6	2-deg/2-deg	JP-7	11	0.0000	0.0000	0.0000	0.0000	0.814	0.701	0.000	Pilot Fuel= Ethylene
		Ramp-Mounted	(HEATED)	16	0.0223	0.0000	0.0000	0.0223	0.882	0.787	0.121	(not heated)
		Pilot		27	0.0217	0.0654	0.0993	0.1864	1.008	1.143	0.506	T_f = 1492 R
				33	0.0215	0.0608	0.0925	0.1748	0.999	1.092	0.454	T_f = 1570 R
				40	0.0209	0.0724	0.1101	0.2034	0.989	1.084	0.451	T_f = 1141 R
293	5.6	2-deg/2-deg	JET-A	11	0.0000	0.0000	0.0000	0.0000	0.802	0.689	0.000	Pilot Fuel= Ethylene
		Ramp-Mounted	+10% TEA	17	0.0221	0.0000	0.0000	0.0221	0.870	0.777	0.126	(not heated)
		Pilot	(HEATED)	30	0.0215	0.0316	0.0480	0.1011	0.963	0.979	0.356	T_f = 1196 R
				32	0.0215	0.0261	0.0397	0.0873	0.928	0.916	0.285	T_f = 1375 R
				34	0.0214	0.0225	0.0341	0.0780	0.920	0.886	0.256	T_f = 1517 R
294	5.6	2-deg/2-deg	JET-A	14	0.0000	0.0000	0.0000	0.0000	0.816	0.714	0.000	Pilot Fuel= Ethylene
		Ramp-Mounted	+10% TEA	19	0.0228	0.0000	0.0000	0.0228	0.886	0.797	0.123	(not heated)
		Pilot	(HEATED)	30	0.0221	0.0737	0.1110	0.2068	1.002	1.193	0.529	T_f = 1226 R
				32	0.0220	0.0609	0.0925	0.1754	0.991	1.121	0.462	T_f = 1406 R
				34	0.0220	0.0613	0.0931	0.1764	0.978	1.067	0.406	T_f = 1480 R

APPENDIX - COMBUSTOR TEST SUMMARY

RUN	M_0	CONTOUR up/dwn	FUEL	BURST	EQUIVALENCE RATIO PILOT	PRIMARY	SECONDARY	TOTAL	$\int PdA/(P_{s0}*\Delta A)$ upstream	dwnstrm	NORMALIZED $\int PdA/(P_{s0}*\Delta A)$	COMMENTS
297	5.6	2-deg/2-deg	ETHYLENE	13	0.0000	0.0000	0.0000	0.0000	1.618	1.390	0.000	SAME SEC INJ
		Ramp-Mounted		27	0.0216	0.0000	0.0000	0.0216	1.714	1.536	0.102	THRU RUN 311
		Pilot		29	0.0216	0.0986	0.0000	0.1202	2.024	2.254	0.504	X_{sec} = 16 in
				31	0.0216	0.0978	0.0709	0.1903	1.908	2.728	0.681	(Two 0.062-in holes)
				33	0.0215	0.0963	0.1186	0.2364	1.830	3.779	1.125	central 0.043-in hole
				35	0.0213	0.0942	0.1565	0.2720	3.920	4.168	1.802	Mode Transition
				37	0.0212	0.0929	0.1894	0.3035	4.545	4.561	2.129	Mode Transition
306	5.6	2-deg/2-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	1.651	1.380	0.000	*** T_o=2200 R
	***	Ramp-Mounted		19	0.0202	0.0000	0.0000	0.0202	1.763	1.548	0.114	
		Pilot		21	0.0202	0.0350	0.0000	0.0552	1.916	1.794	0.257	
				25	0.0201	0.0823	0.0000	0.1024	2.185	2.381	0.633	
				28	0.0201	0.0742	0.1411	0.2354	4.272	3.976	1.793	Mode Transition
				34	0.0200	0.0666	0.1272	0.2138	3.971	3.847	1.660	Mode Transition
				37	0.0200	0.0651	0.0876	0.1727	2.948	3.485	1.262	Mode Transition
312	5.6	2-deg/2-deg	ETHYLENE	15	0.0000	0.0000	0.0000	0.0000	1.658	1.452	0.000	SAME SEC INJ
		Dual Ramp-		22	0.0446	0.0000	0.0000	0.0446	2.191	1.840	0.266	THRU RUN 314
		Mounted Pilots		25	0.0444	0.0476	0.0000	0.0920	2.464	2.227	0.435	X_{sec} = 16 in
				28	0.0440	0.1076	0.0000	0.1516	3.471	2.709	0.887	(Three 0.062-in holes)
				31	0.0438	0.0776	0.0000	0.1214	2.958	2.410	0.611	
				33	0.0436	0.1600	0.0000	0.2036	3.940	3.050	1.138	Mode Transition
				37	0.0435	0.2013	0.0000	0.2448	4.477	3.575	1.507	Mode Transition
313	5.6	2-deg/2-deg	ETHYLENE	13	0.0000	0.0000	0.0000	0.0000	1.745	1.443	0.000	
		Dual Ramp-		18	0.0442	0.0000	0.0000	0.0442	2.211	1.839	0.263	
		Mounted Pilots		23	0.0442	0.1047	0.0000	0.1489	3.543	2.706	0.880	
				25	0.0440	0.1022	0.0796	0.2258	4.177	2.981	1.153	Mode Transition
				26	0.0438	0.1041	0.1142	0.2621	4.499	3.360	1.360	Mode Transition
				27	0.0437	0.1053	0.1378	0.2868	4.947	3.671	1.571	Mode Transition
				29	0.0436	0.1061	0.1653	0.3150	5.343	4.044	1.826	Unstart
				30	0.0435	0.1063	0.1545	0.3043	5.296	4.050	1.814	Unstart
314	5.6	2-deg/3-deg	ETHYLENE	12	0.0000	0.0000	0.0000	0.0000	1.754	1.257	0.000	
		Dual Ramp-		15	0.0436	0.0000	0.0000	0.0436	2.212	1.530	0.245	
		Mounted Pilots		19	0.0438	0.1135	0.0000	0.1573	3.734	2.202	0.838	
				22	0.0435	0.1122	0.1043	0.2600	4.393	2.567	1.194	Mode Transition
				24	0.0433	0.1114	0.1385	0.2932	5.169	2.912	1.466	Mode Transition
				26	0.0431	0.1110	0.1682	0.3223	6.296	3.273	1.854	Unstart- P_{s0} changed
				30	0.0430	0.1110	0.1207	0.2747	4.934	2.849	1.405	Mode Transition
315	5.6	2-deg/3-deg	ETHYLENE	12	0.0000	0.0000	0.0000	0.0000	1.885	1.250	0.000	SAME SEC INJ
		Dual Ramp-		17	0.0438	0.0000	0.0000	0.0438	2.355	1.545	0.252	THRU RUN 325
		Mounted Pilots		24	0.0434	0.1114	0.0000	0.1548	3.608	2.208	0.816	Xsec = 25 in
				28	0.0430	0.1111	0.0790	0.2331	3.978	2.579	1.082	(Three 0.062-in holes)
				30	0.0429	0.1112	0.1237	0.2778	4.215	2.786	1.255	
				32	0.0428	0.1114	0.1655	0.3197	4.566	2.922	1.432	Mode Transition
				34	0.0428	0.1116	0.1838	0.3382	4.620	3.013	1.495	for bursts 28-34
316	5.6	2-deg/3-deg	ETHYLENE	13	0.0000	0.0000	0.0000	0.0000	1.892	1.246	0.000	
		Dual Ramp-		17	0.0438	0.0000	0.0000	0.0438	2.368	1.559	0.261	
		Mounted Pilots		21	0.0437	0.1322	0.0000	0.1759	3.850	2.282	0.890	
				23	0.0431	0.1347	0.1176	0.2954	4.620	2.711	1.309	
				25	0.0428	0.1337	0.1630	0.3395	4.789	2.992	1.515	Mode Transition
				27	0.0425	0.1331	0.1909	0.3665	4.802	3.188	1.623	for bursts 23-31
				31	0.0422	0.1521	0.1783	0.3726	4.826	3.194	1.627	
317	5.6	2-deg/2-deg	ETHYLENE	12	0.0000	0.0000	0.0000	0.0000	1.869	1.455	0.000	
		Dual Ramp-		15	0.0448	0.0000	0.0000	0.0448	2.333	1.824	0.241	
		Mounted Pilots		21	0.0436	0.1295	0.0000	0.1731	3.846	2.830	0.959	
				23	0.0431	0.1270	0.0818	0.2519	4.053	3.379	1.235	Mode Transition
				25	0.0428	0.1257	0.1156	0.2841	4.383	3.527	1.407	for bursts 23-29
				27	0.0425	0.1251	0.1680	0.3356	4.801	4.107	1.755	
				29	0.0424	0.1254	0.1841	0.3519	4.906	4.283	1.829	
318	5.6	2-deg/2-deg	ETHYLENE	10	0.0000	0.0000	0.0000	0.0000	1.851	1.444	0.000	
		Dual Ramp-		15	0.0442	0.0000	0.0000	0.0442	2.355	1.856	0.273	
		Mounted Pilots		23	0.0435	0.1803	0.0000	0.2238	4.506	3.499	1.438	Mode Transition
				24	0.0435	0.1814	0.0321	0.2570	4.827	3.633	1.557	for bursts 23-26
				25	0.0435	0.1815	0.0785	0.3035	5.189	3.947	1.727	
				26	0.0434	0.1814	0.1254	0.3502	5.407	4.504	1.989	
				27	0.0433	0.1810	0.1728	0.3971	4.989	4.432	1.859	Unstart
				28	0.0431	0.1806	0.1490	0.3727	4.147	3.699	1.398	Unstart
319	5.6	2-deg/3-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	1.979	1.268	0.000	
		Dual Ramp-		13	0.0447	0.0000	0.0000	0.0447	2.319	1.500	0.206	
		Mounted Pilots		17	0.0444	0.1697	0.0000	0.2141	4.416	2.554	1.146	
				19	0.0443	0.1690	0.1135	0.3268	5.192	2.942	1.447	Mode Transition
				20	0.0443	0.1688	0.1392	0.3523	5.323	3.109	1.562	for bursts 19-28
				22	0.0442	0.1689	0.1887	0.4018	5.378	3.354	1.705	
				24	0.0441	0.1689	0.2169	0.4299	5.407	3.516	1.799	
				28	0.0440	0.1692	0.2044	0.4176	5.089	3.289	1.624	

APPENDIX - COMBUSTOR TEST SUMMARY

RUN	M_0	CONTOUR up/dwn	FUEL	BURST	PILOT	EQUIVALENCE RATIO PRIMARY	EQUIVALENCE RATIO SECONDARY	TOTAL	$\int PdA/(P_{\infty}*\Delta A)$ upstream	$\int PdA/(P_{\infty}*\Delta A)$ dwnstrm	NORMALIZED $\int PdA/(P_{\infty}*\Delta A)$	COMMENTS
320	5.6	2.5-deg/2.5-deg	ETHYLENE	10	0.0000	0.0000	0.0000	0.0000	1.373	1.033	0.000	Pilot and primary
		Dual Ramp-		14	0.0444	0.0000	0.0000	0.0444	1.556	1.340	0.206	fuel only
		Mounted Pilots		18	0.0441	0.0966	0.0000	0.1407	1.742	1.790	0.489	
				21	0.0437	0.1502	0.0000	0.1939	2.008	2.409	0.895	
				24	0.0434	0.1859	0.0000	0.2293	3.103	2.591	1.308	Mode Transition
				26	0.0434	0.2073	0.0000	0.2507	3.474	2.748	1.455	Mode Transition
				31	0.0433	0.1979	0.0000	0.2412	3.287	2.685	1.391	Mode Transition
321	5.6	2.5-deg/2.5-deg	ETHYLENE	9	0.0000	0.0000	0.0000	0.0000	1.391	1.050	0.000	
		Dual Ramp-		12	0.0442	0.0000	0.0000	0.0442	1.554	1.343	0.196	
		Mounted Pilots		16	0.0438	0.1693	0.0000	0.2131	2.968	2.439	1.193	Mode Transition
				21	0.0430	0.0000	0.1627	0.2057	1.556	2.965	1.040	Primary fuel off
				23	0.0428	0.0000	0.2084	0.2512	2.262	3.443	1.477	
				25	0.0427	0.0000	0.2384	0.2811	2.703	3.773	1.765	
322	5.6	2.5-deg/2.5-deg	ETHYLENE	9	0.0000	0.0000	0.0000	0.0000	1.374	1.030	0.000	
		Dual Ramp-		12	0.0440	0.0000	0.0000	0.0440	1.531	1.287	0.180	
		Mounted Pilots		16	0.0445	0.2338	0.0000	0.2783	3.726	2.781	1.559	Mode transition
				19	0.0434	0.2243	0.1187	0.3864	3.832	3.070	1.763	for bursts 16-28
				21	0.0429	0.2092	0.1903	0.4424	3.775	3.296	1.865	
				23	0.0427	0.1981	0.2234	0.4642	3.826	3.402	1.945	
				26	0.0424	0.1893	0.2028	0.4345	3.854	3.351	1.910	
				28	0.0422	0.1853	0.1859	0.4134	3.839	3.310	1.881	
327	7.0	2-deg/3-deg	ETHYLENE	13	0.0000	0.0000	0.0000	0.0000	1.886	1.244	0.000	SAME SEC INJ
		Ramp-Mounted		20	0.0152	0.0000	0.0000	0.0152	1.949	1.303	0.044	THRU RUN 330
		Pilot		24	0.0216	0.0000	0.0000	0.0216	1.906	1.336	0.061	X_{sec} = 16 in
				27	0.0210	0.0219	0.0000	0.0429	1.960	1.403	0.112	(Three 0.062-in holes)
				28	0.0215	0.0418	0.0000	0.0633	2.017	1.479	0.150	
				29	0.0218	0.0727	0.0000	0.0945	2.134	1.689	0.291	Pilot and primary
				30	0.0211	0.0825	0.0000	0.1036	2.164	1.949	0.430	fuel only
				33	0.0216	0.0818	0.0000	0.1034	2.153	1.875	0.380	
328	7.0	2-deg/3-deg	ETHYLENE	13	0.0000	0.0000	0.0000	0.0000	1.896	1.236	0.000	Pilot and secondary
		Ramp-Mounted		19	0.0228	0.0000	0.0000	0.0228	1.937	1.344	0.074	fuel only
		Pilot		22	0.0225	0.0000	0.0000	0.0225	1.927	1.344	0.072	
				24	0.0231	0.0000	0.0688	0.0919	2.070	1.585	0.214	
				26	0.0231	0.0000	0.1062	0.1293	2.198	2.030	0.457	
				29	0.0227	0.0000	0.1500	0.1727	2.219	2.413	0.747	
329	7.0	2-deg/2-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	1.808	1.392	0.000	
		Ramp-Mounted		15	0.0229	0.0000	0.0000	0.0229	1.953	1.556	0.084	
		Pilot		18	0.0225	0.0515	0.0000	0.0740	2.070	1.875	0.201	
				20	0.0227	0.0945	0.0000	0.1172	2.224	2.443	0.517	
				22	0.0221	0.0920	0.0515	0.1656	2.216	2.666	0.606	
				23	0.0222	0.0922	0.1161	0.2305	2.111	3.221	0.754	
				24	0.0224	0.0916	0.1717	0.2857	2.135	3.731	1.009	
330	7.0	2-deg/3-deg	ETHYLENE	11	0.0000	0.0000	0.0000	0.0000	1.972	1.234	0.000	
		Ramp-Mounted		16	0.0243	0.0000	0.0000	0.0243	2.009	1.369	0.106	
		Pilot		18	0.0252	0.0544	0.0000	0.0796	2.219	1.594	0.232	
				20	0.0241	0.0944	0.0000	0.1185	2.274	2.172	0.600	
				21	0.0244	0.0950	0.0599	0.1793	2.271	2.303	0.673	
				22	0.0250	0.0973	0.1354	0.2577	2.236	2.603	0.819	
				23	0.0246	0.0952	0.1828	0.3026	2.254	2.989	1.034	
				24	0.0240	0.0906	0.1783	0.2929	2.255	3.020	1.056	

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13. ABSTRACT *(Maximum 200 words)*

The United Technologies Research Center conducted an experimental program to develop technology for a hydrocarbon-fueled ramjet/scramjet engine for operation at flight Mach numbers up to 7. As part of this program, connected-pipe combustion tests of key pilot and fuel injector components were performed in a variable-geometry two-dimensional test section over a range of combustor entrance conditions simulating the intended flight regime. A novel supersonic-inlet, air-breathing pilot was developed under the program that also incorporates an external mainstream fuel injector which serves as a primary fuel injection stage for the supersonic combustor.

In previous tests at simulated Mach 5.6 flight conditions (comprising a combustor entrance Mach number of 3.0), it was demonstrated that the pilot promoted efficient combustion of gaseous ethylene that was injected into the supersonic mainstream flow as a primary fuel. The idea of using the air-breathing pilot and distributed secondary fuel injection to achieve efficient supersonic combustion of ethylene over a wide range of equivalence ratios was also experimentally demonstrated; during tests with staged fuel injection, high secondary fuel combustion efficiencies were achieved and smooth transitions from fully supersonic to mixed mode (supersonic/subsonic) operation were demonstrated at high overall equivalence ratios. The air-breathing pilot was also shown to effectively isolate the inlet from the combustion process even at the high combustor pressures experienced during mixed mode operation. Most of the testing was done with gaseous ethylene fuel which was chosen to simulate both prevaporized liquid fuels and the gaseous products of the endothermic reaction of liquid hydrocarbon fuels. Limited combustor testing was done with liquid hydrocarbon fuels. Recent work, which is the subject of this report, was done to expand the related data base with liquid hydrocarbon fuels and to investigate the effects of a wider variety of combustor configurations and entrance conditions on component and combustor performance.

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